

A SHARP LOOK AT FUTURE NODES OF EUV LITHOGRAPHY

SHARP High-NA actinic Reticle Review Project

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Kenneth Goldberg, Patrick Naulleau

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Lawrence Berkeley National Lab, Berkeley, June 13

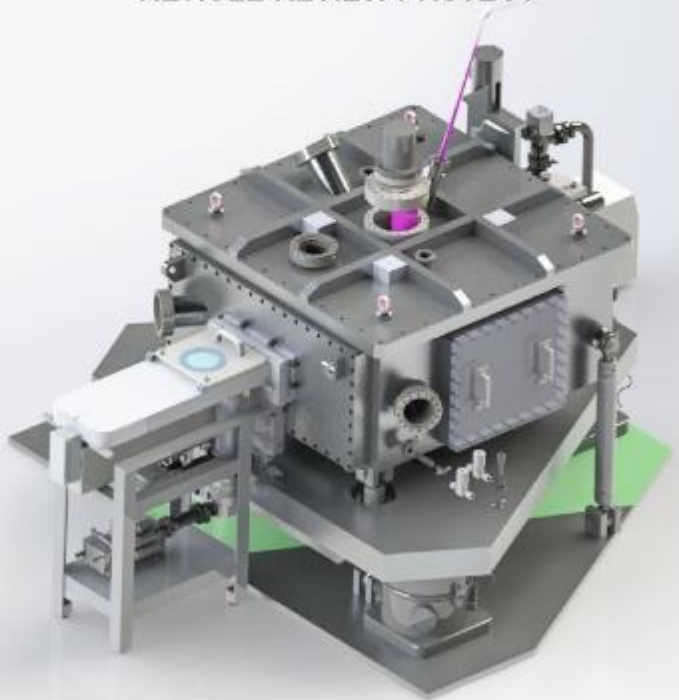


SHARP



SHARP

SEMICONDUCTOR HIGH-NA ACTINIC
RETICLE REVIEW PROJECT



Source: Synchrotron

Optics: Zoneplate lenses

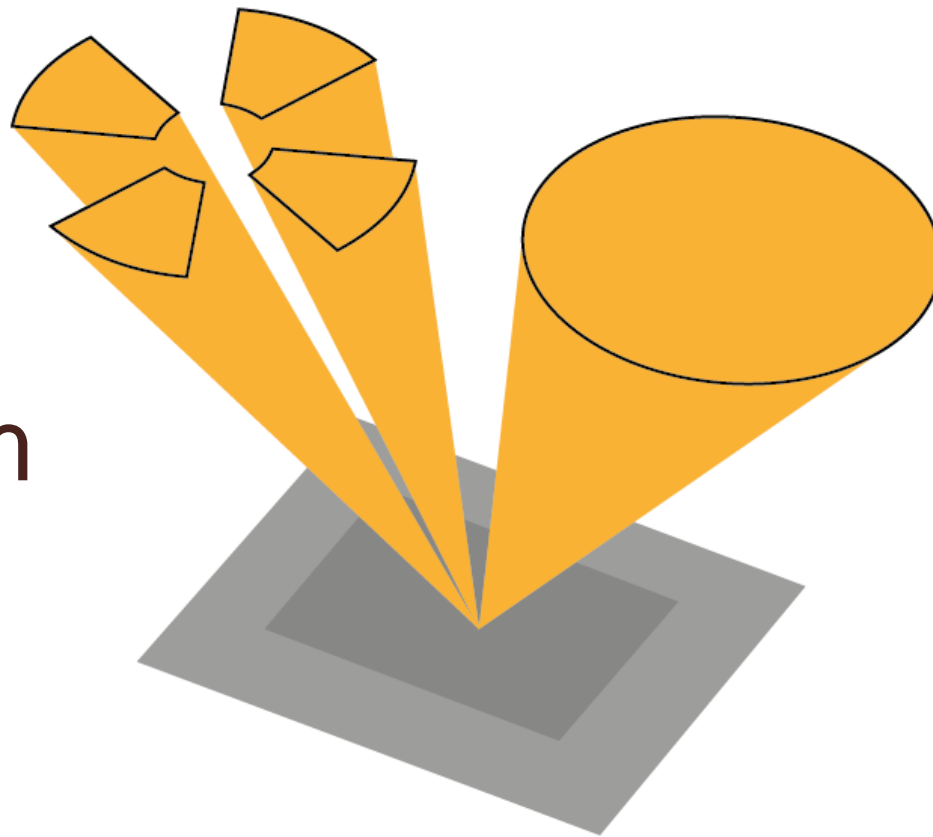
4×NA: 0.25–0.625

Sigma: Programmable

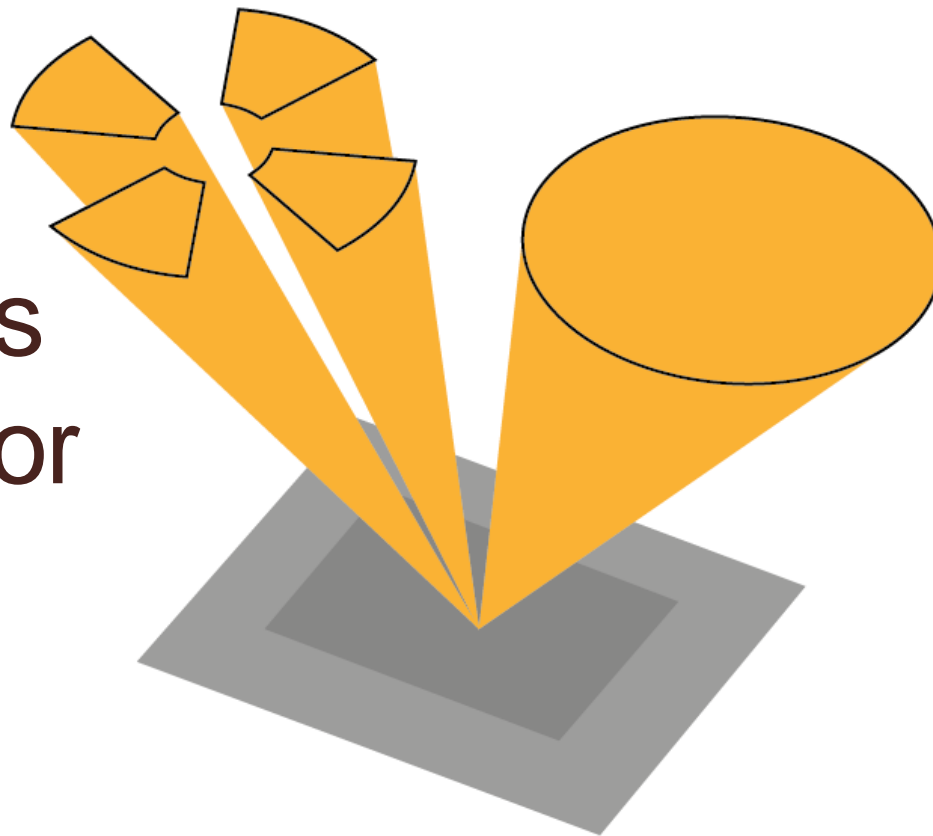
Navigation: 2- μm position accuracy

Throughput: up to 24 sites/hour

Source
angular
spectrum

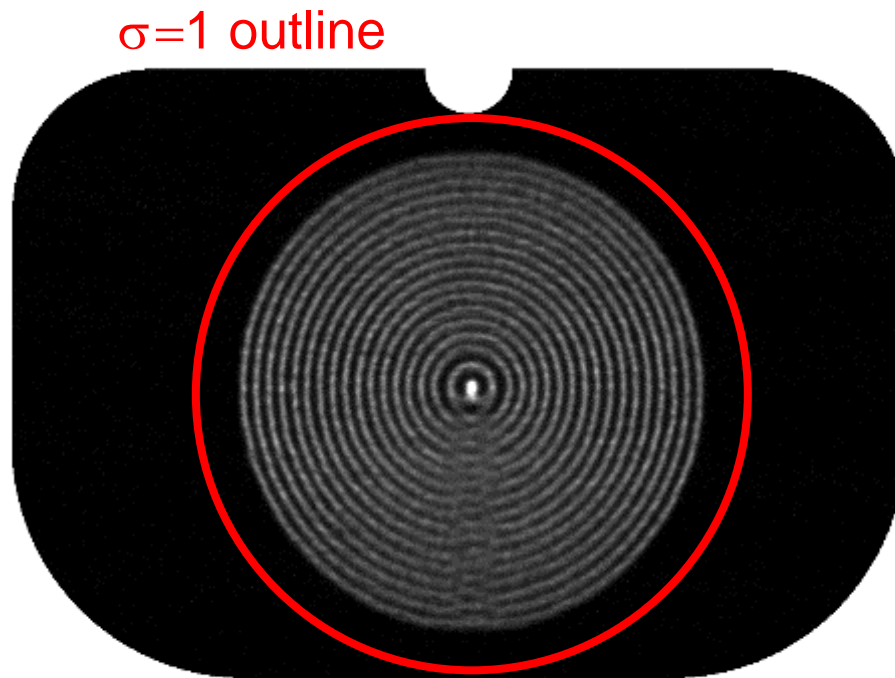


Fourier
synthesis
illuminator



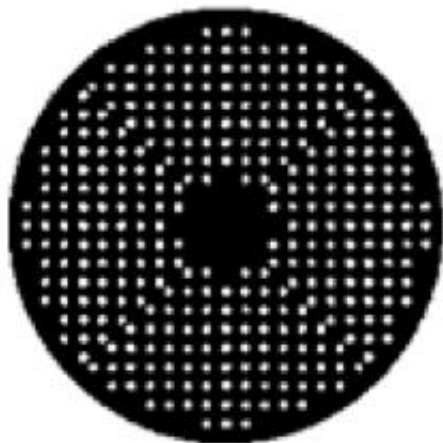
Illuminator angular range

- 0.625 4xNA
10° CRA
 $\sigma=0.8$



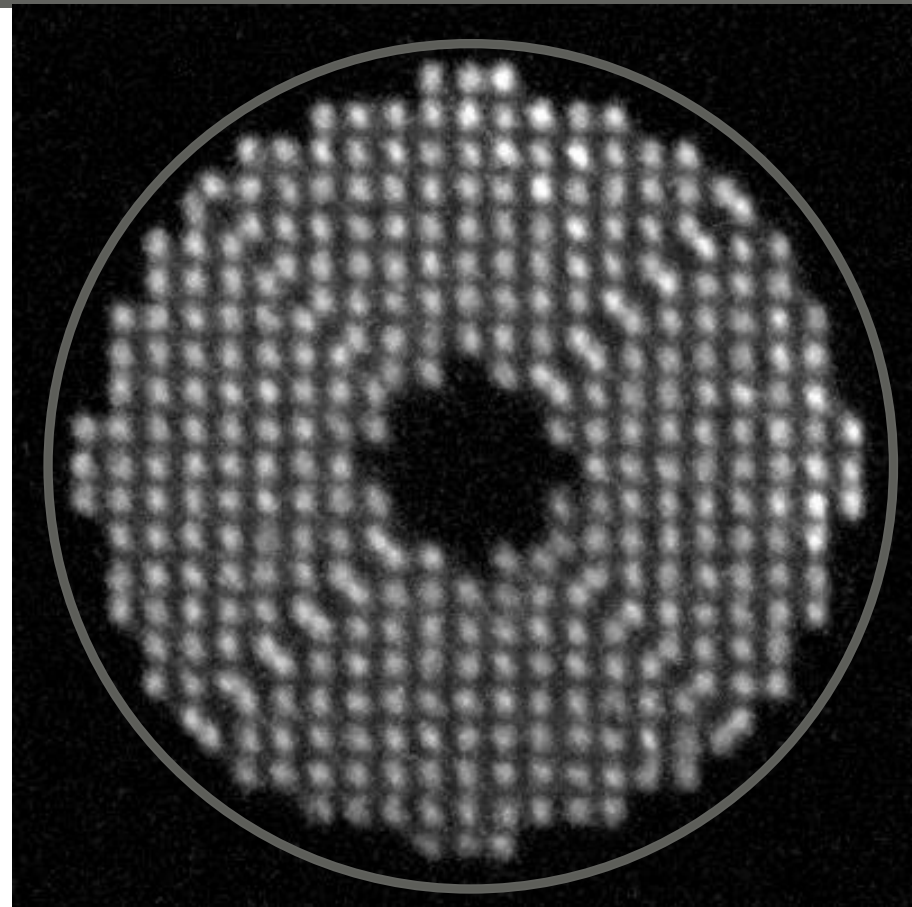
Pupil fill

- Conventional
- 0.33 4xNA, 6° CRA



Liu, SPIE 90480Q (2014)

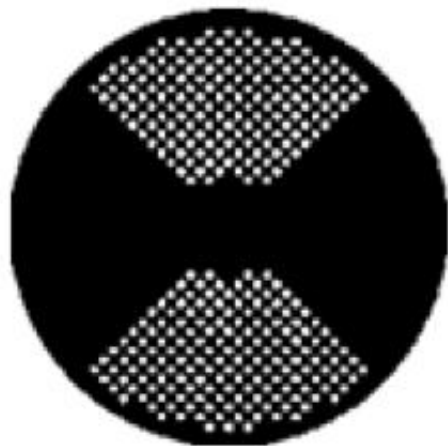
Pupil diagram



YAG image, 4mm below focus

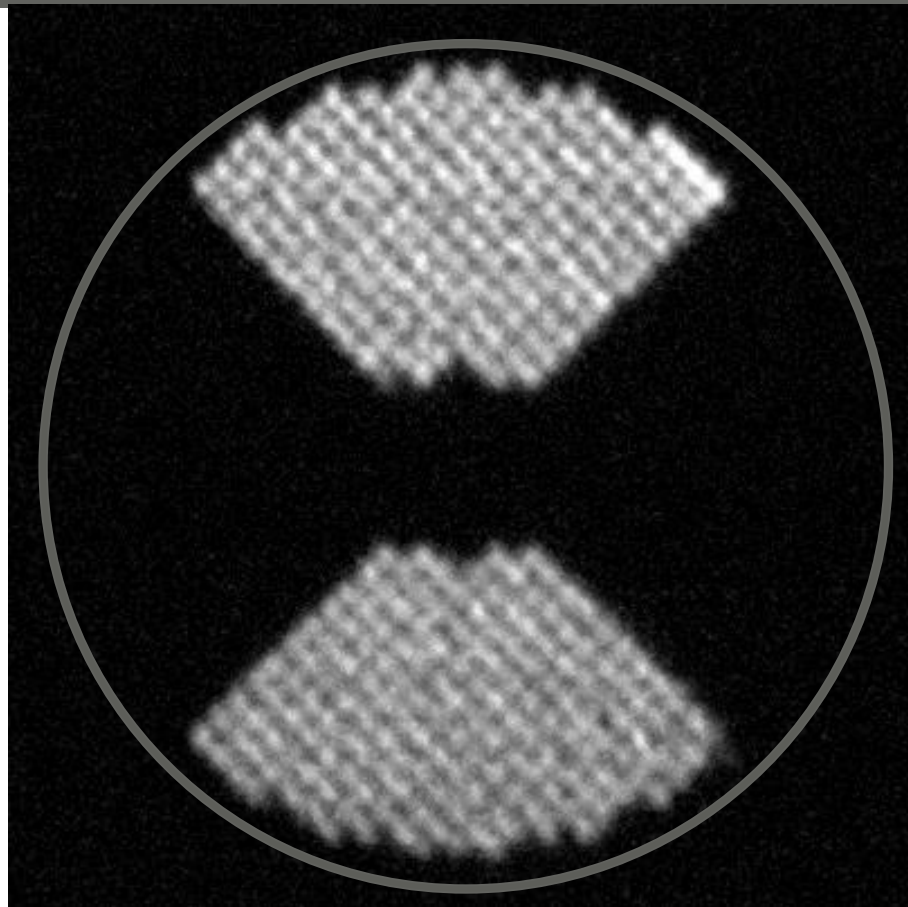
Pupil fill

- Crosspole
- 0.33 4xNA, 6° CRA



Liu, SPIE 90480Q (2014)

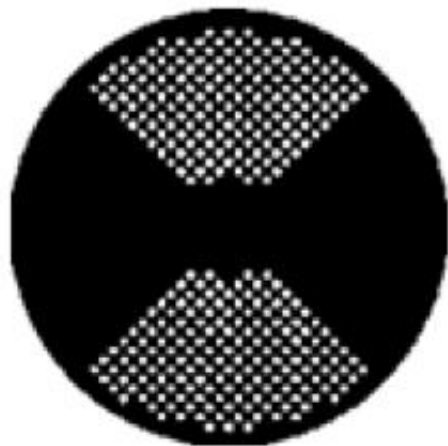
Pupil diagram



YAG image, 4mm below focus

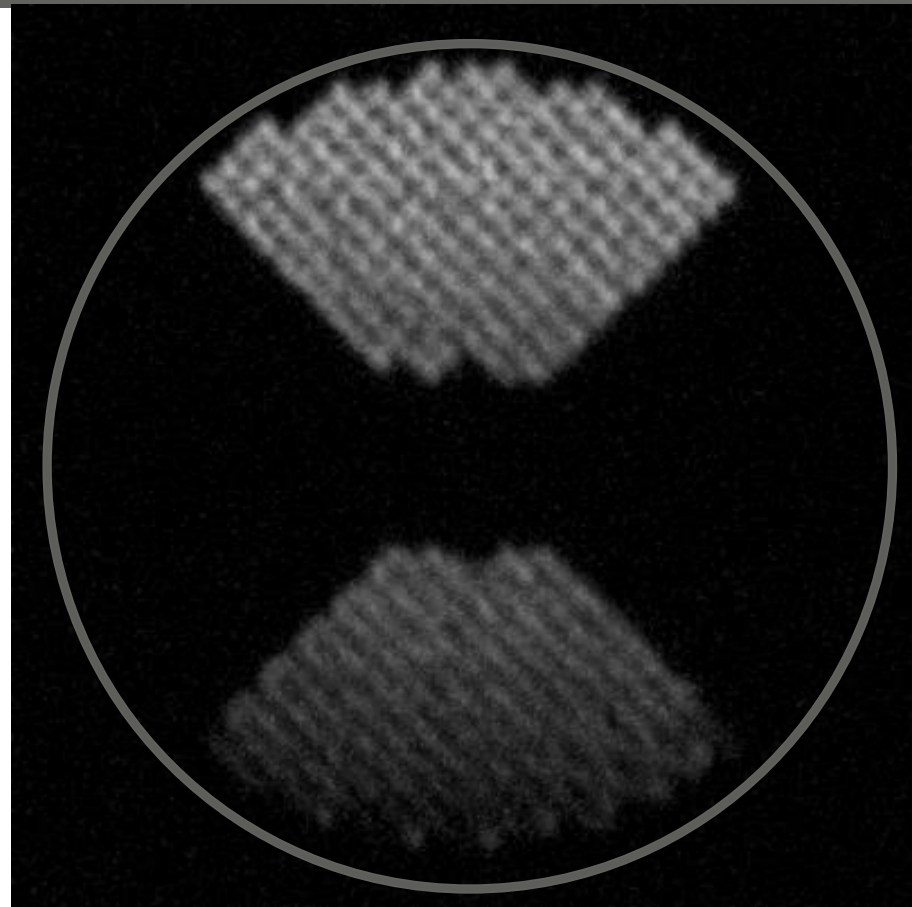
Pupil fill

- Crosspole
- 0.33 4xNA, 6° CRA



Liu, SPIE 90480Q (2014)

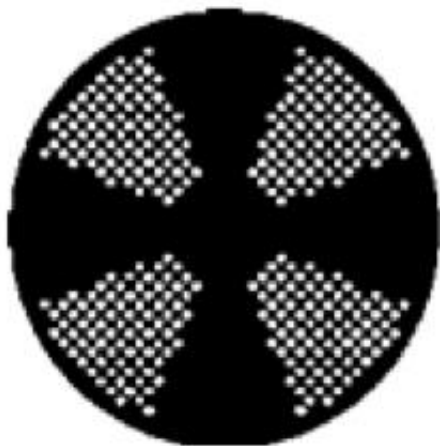
Pupil diagram



Modulation of flux in pupil channels

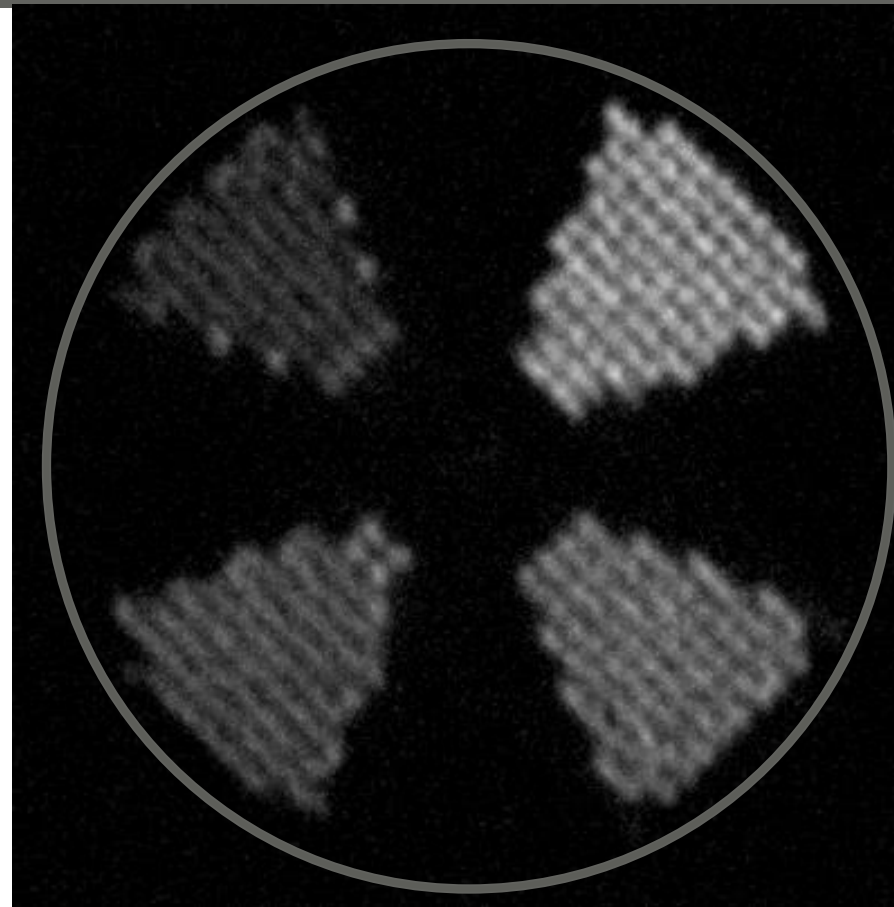
Pupil fill

- Quasar
- 0.33 4xNA, 6° CRA



Liu, SPIE 90480Q (2014)

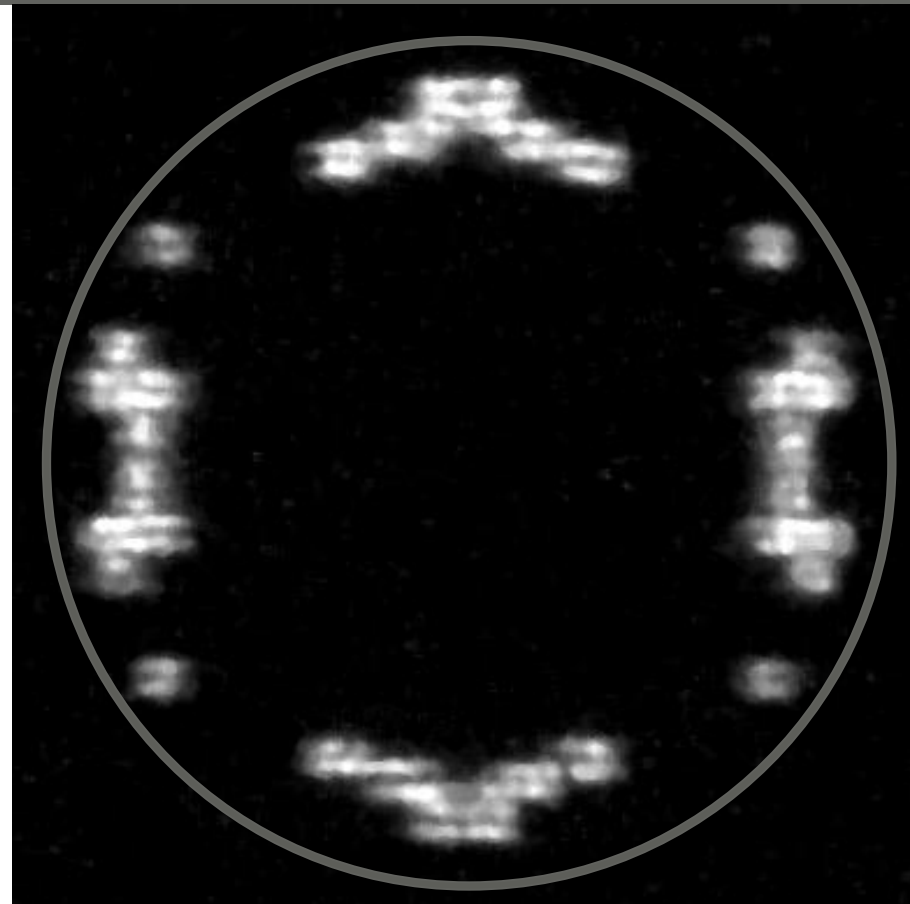
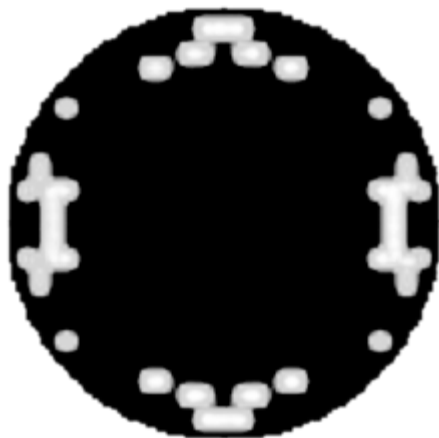
Pupil diagram



Modulation of flux in pupil channels

Pupil fill

- Freeform Source
- 0.33 4xNA, 6° CRA



Pupil diagram

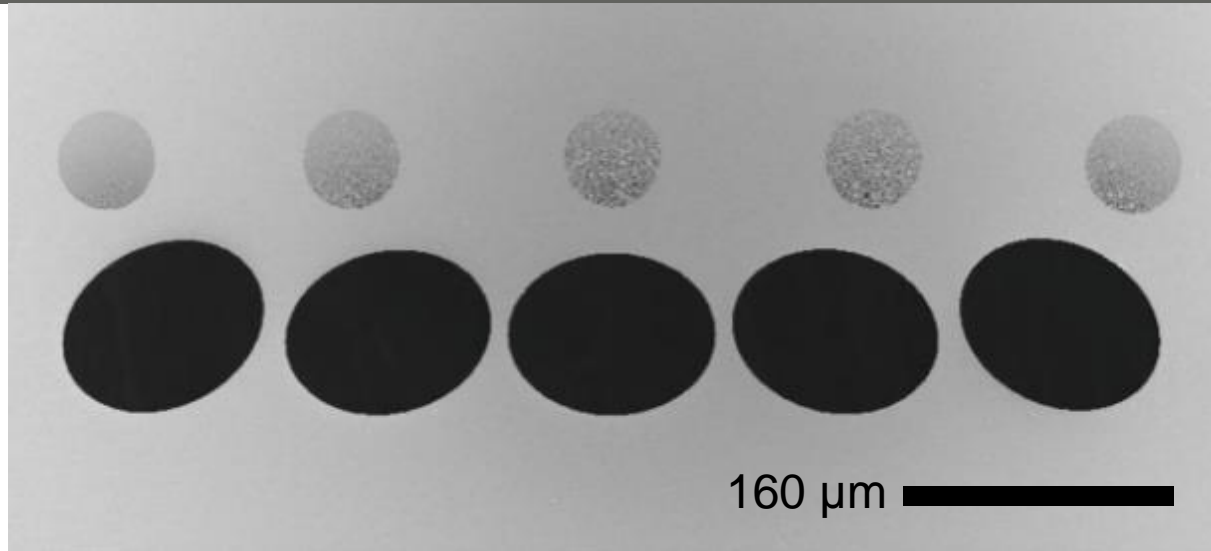
- Gold pattern on Si_3N_4 -membranes
- Magnetic mounting
- Kinematic positioning

2 mm

Zoneplates

Standard Zoneplates:

- 0.25 to 0.625 4xNA
- 6° to 10° CRA
- 5 azimuthal angles



Chip B

- Zernike Phase Contrast
- Differential Interference Contrast
- Stereoscopic imaging
- Cubic Phase Modulation

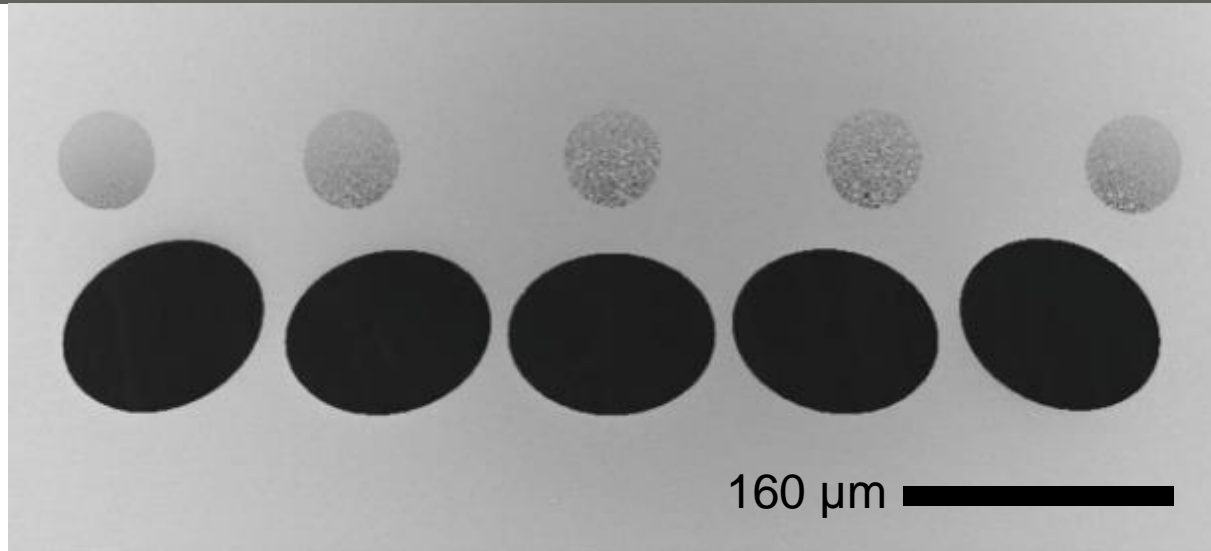
0.625 4xNA:

- 22-nm hp resolution on the mask
- 5.5 nm hp resolution wafer scale (for a 4x system)

Zoneplates

Standard Zoneplates:

- 0.25 to 0.625 4xNA
- 6° to 10° CRA
- 5 azimuthal angles

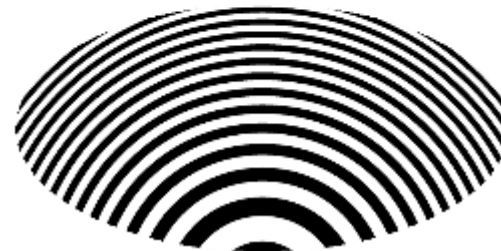


Chip B

- Zernike Phase Contrast
- Differential Interference Contrast
- Stereoscopic imaging
- Cubic Phase Modulation

Chip C

- Elliptical zoneplates



Thin-absorber wafer mask

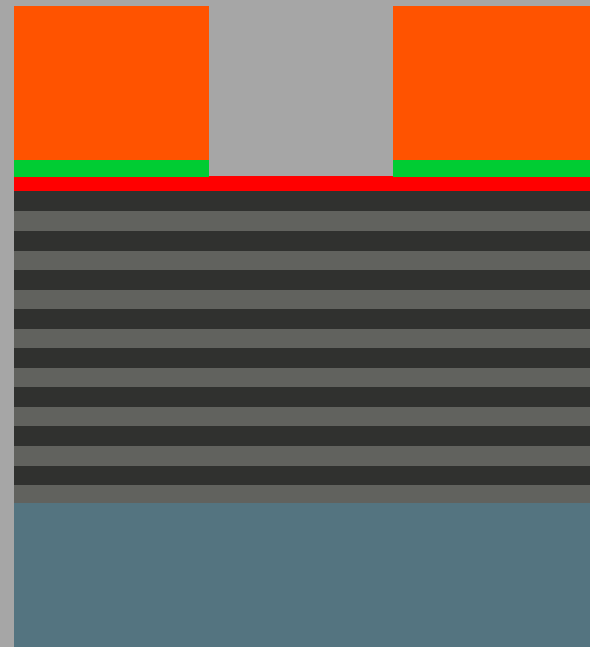
40-nm Nickel absorber

Chrome

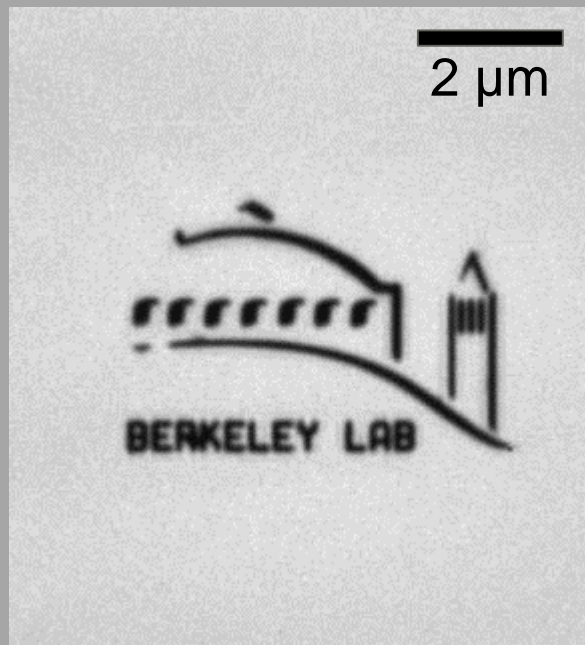
Ruthenium

Mo/Si Multilayer

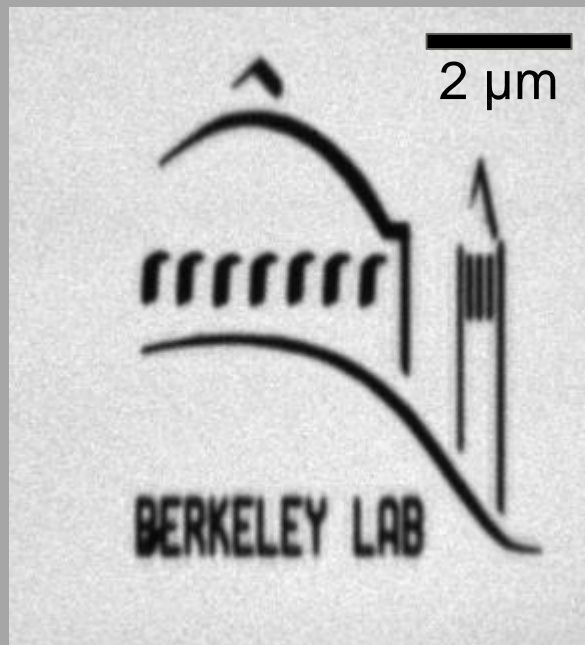
Silicon wafer



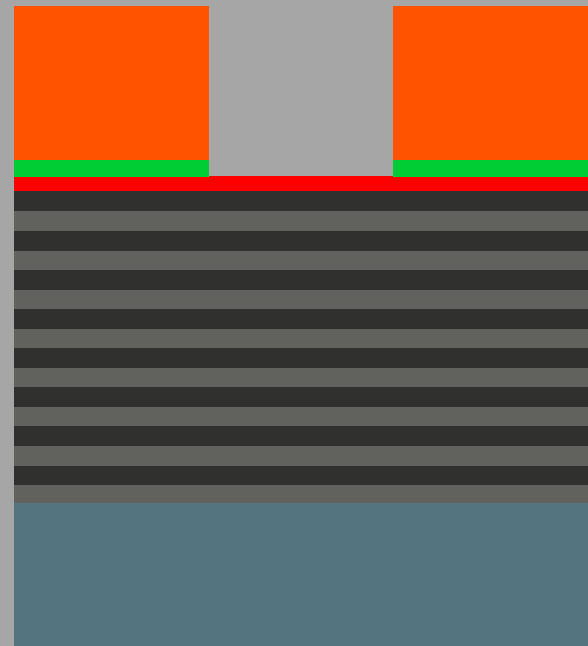
Thin-absorber wafer mask



4x/4x



4x/8x



Comparison of absorbers

Future Study

- Two photomasks with identical patterns
- Mask SEM characterization



Comparison of absorbers

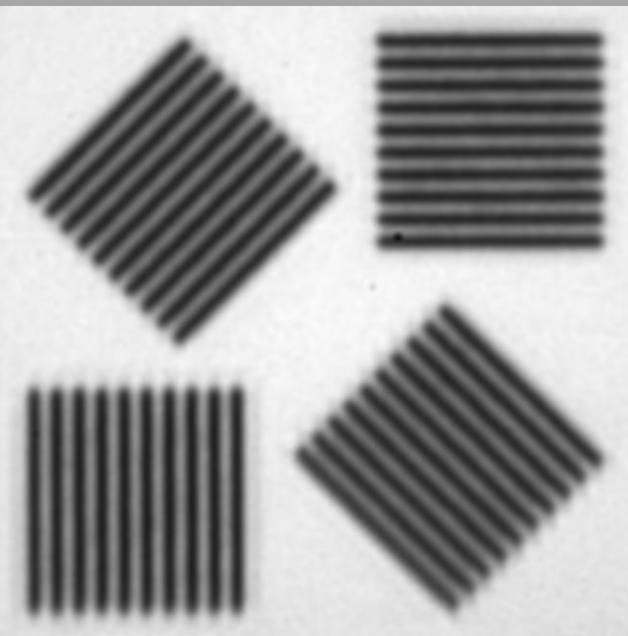
Initial Study

- Identify comparable patterns on available photomasks



Patterns

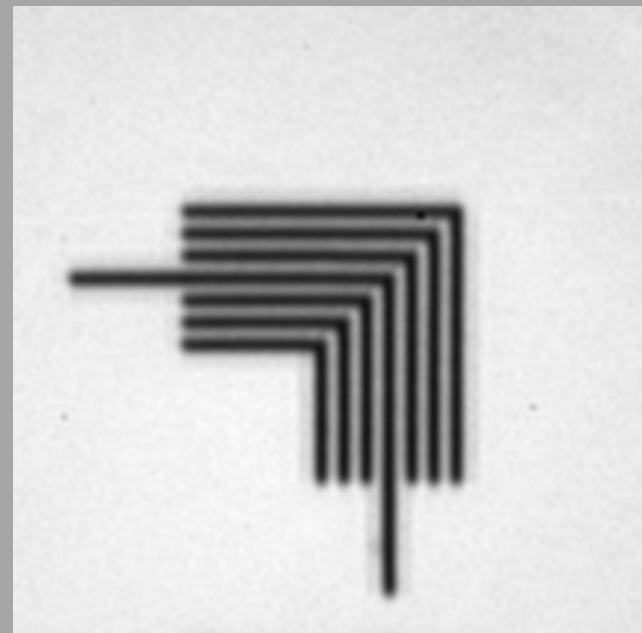
- 0.33 4x NA
- Quasar illumination



— 200 nm (1x)

- Ta-based

- 22.5 nm CD (1x)

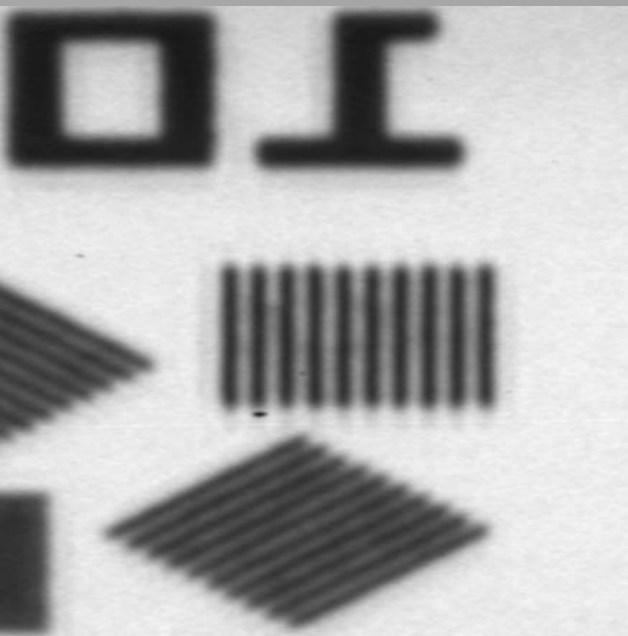


— 200 nm (1x)

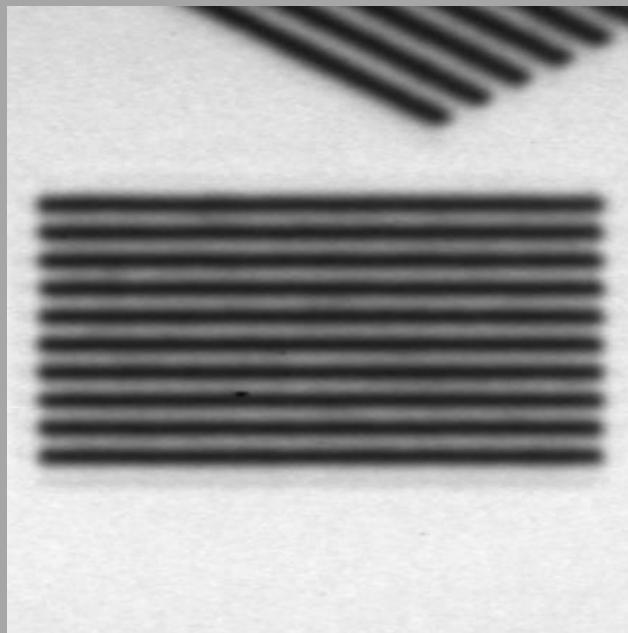
- Nickel

Patterns

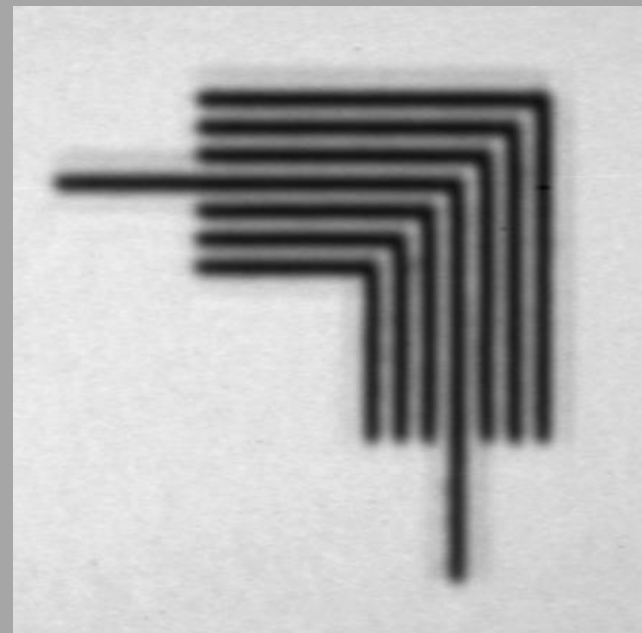
- 0.55 4x/8x NA
- Quasar illumination
- 12.5 nm CD (1x)



- 100 nm (1x)
- Ta-based V



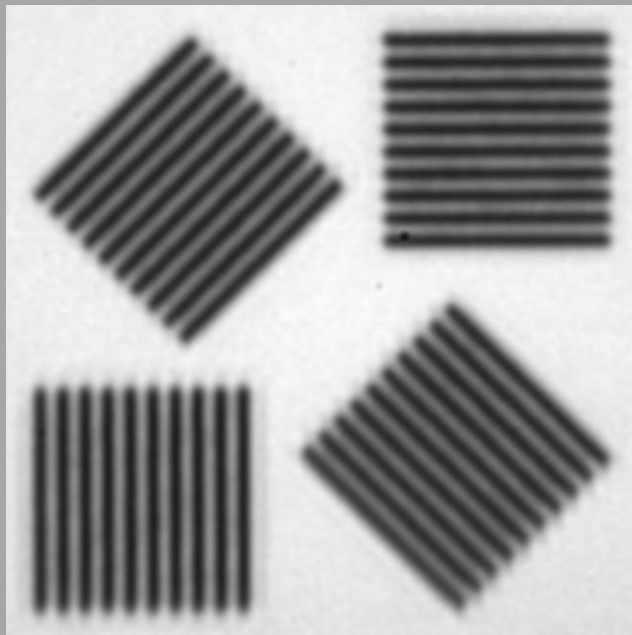
- 100 nm (1x)
- Ta-based H



- 100 nm (1x)
- Nickel

Contrast and NILS

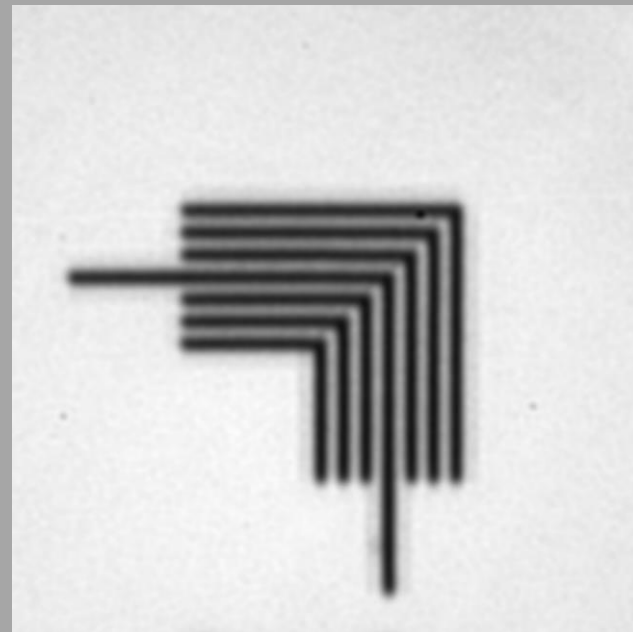
- 0.33 4x NA
- Quasar illumination



22.5 nm
CD (1x)

— 200 nm (1x)

- Ta-based

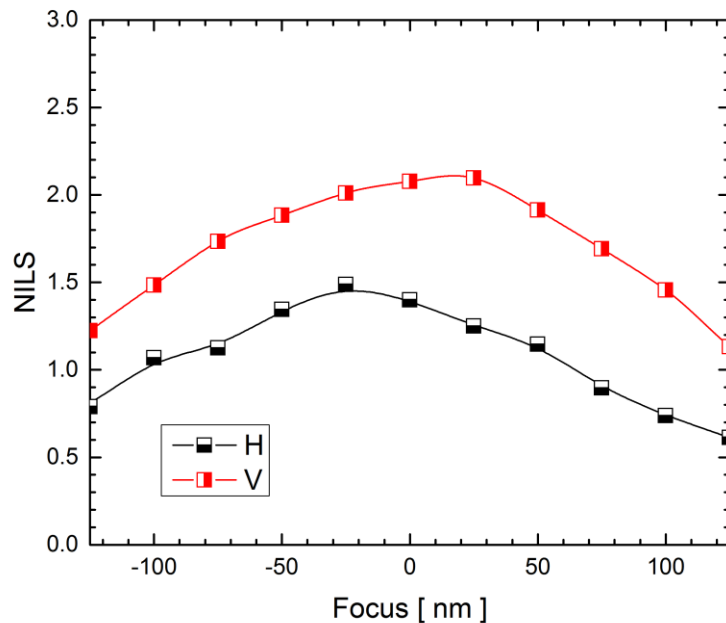


— 200 nm (1x)

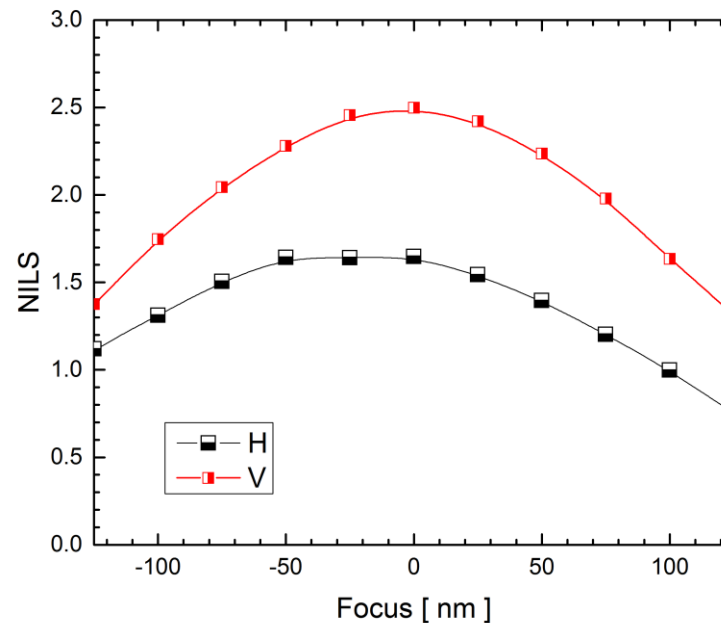
- Nickel

Contrast and NILS

- 0.33 4x NA
- Quasar illumination

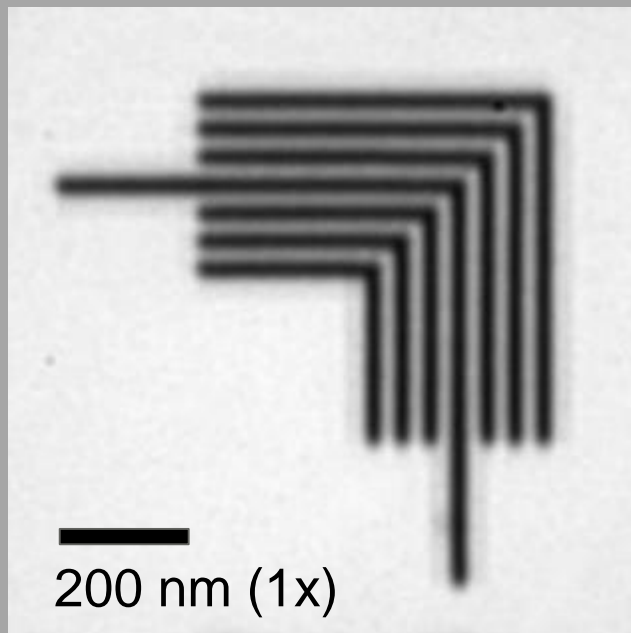


■ Ta-based



■ Nickel

Contrast and NILS

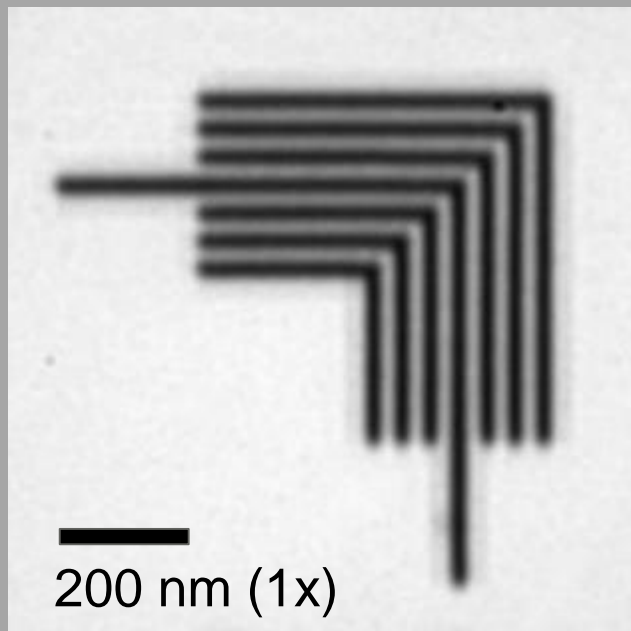


- 0.33 4x NA
- Nickel

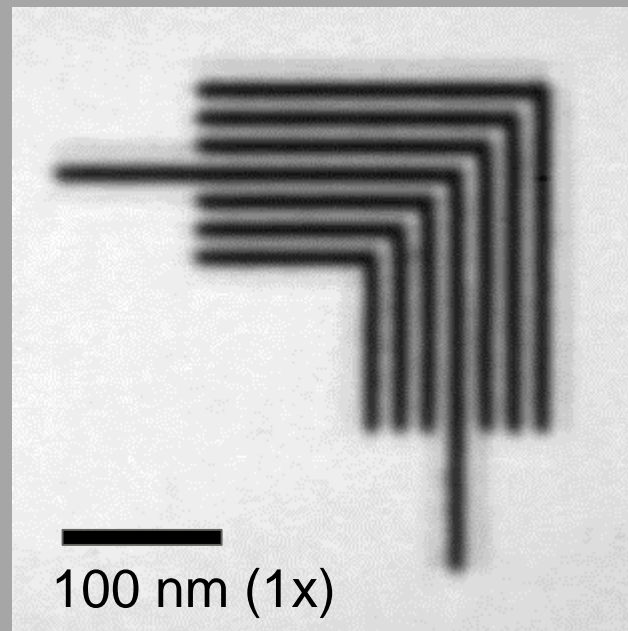
0.33 4xNA:

- higher on vertical features

Contrast and NILS

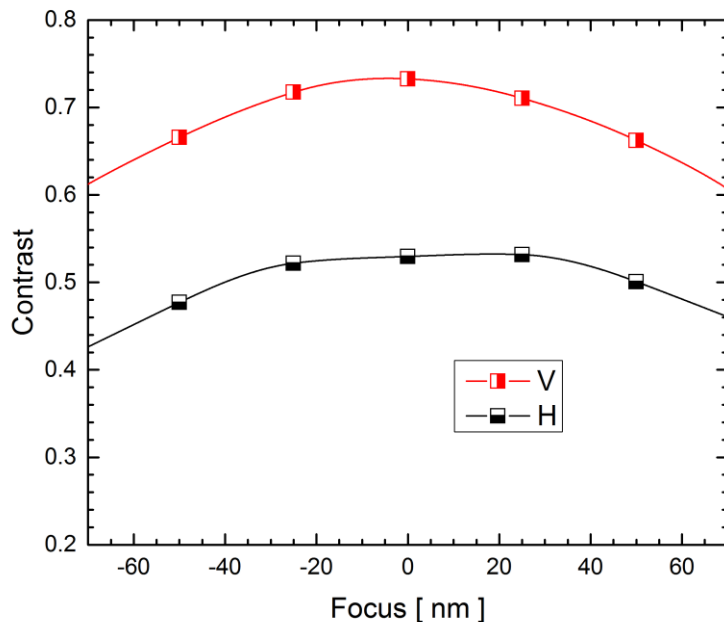


- 0.33 4x NA
- higher contrast in V

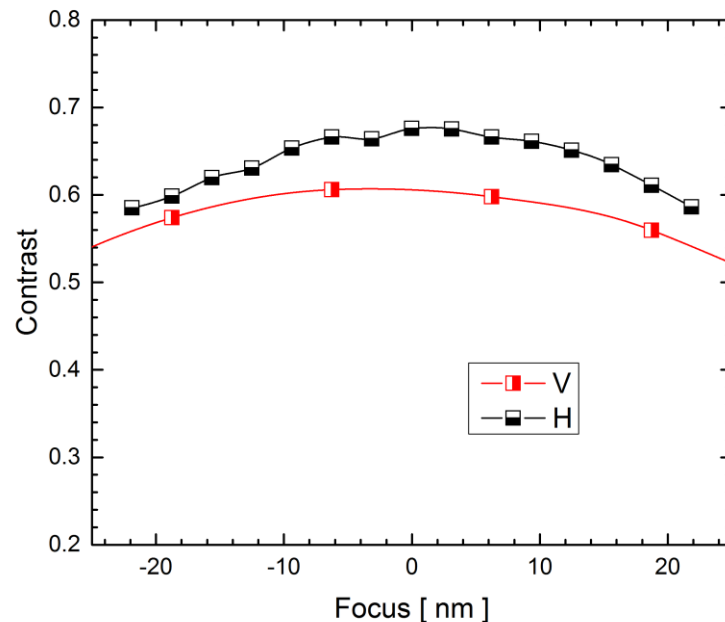


- 0.55 4x/8x NA
- higher contrast in H

Contrast and NILS

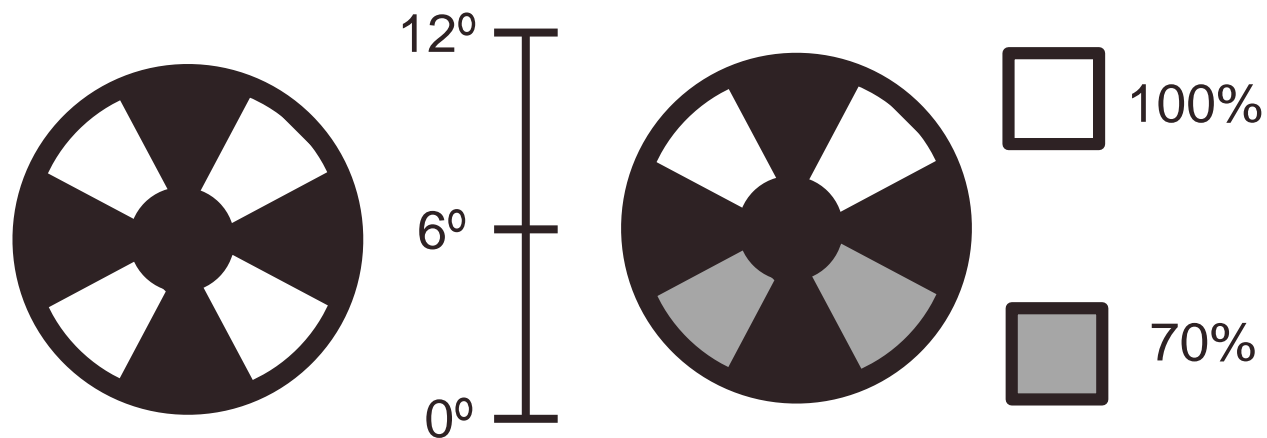


- 0.33 4x NA
- higher contrast in V



- 0.55 4x/8x NA
- higher contrast in H

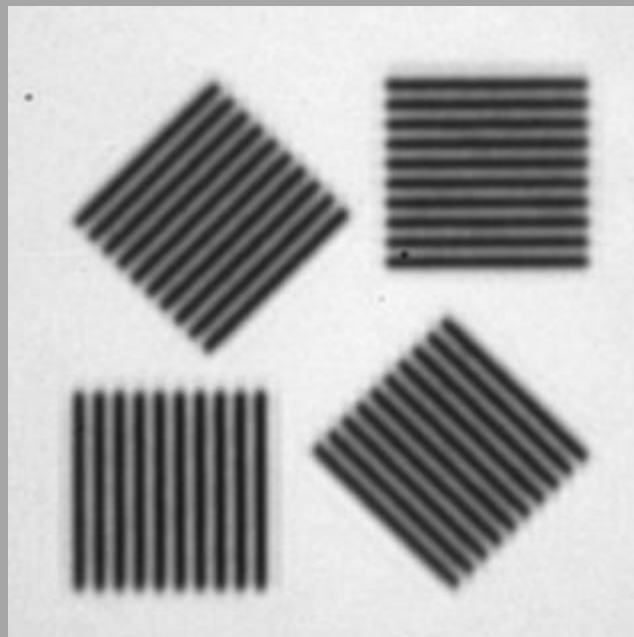
Optimized source



- 0.33 4xNA, regular mask
- balanced Quasar

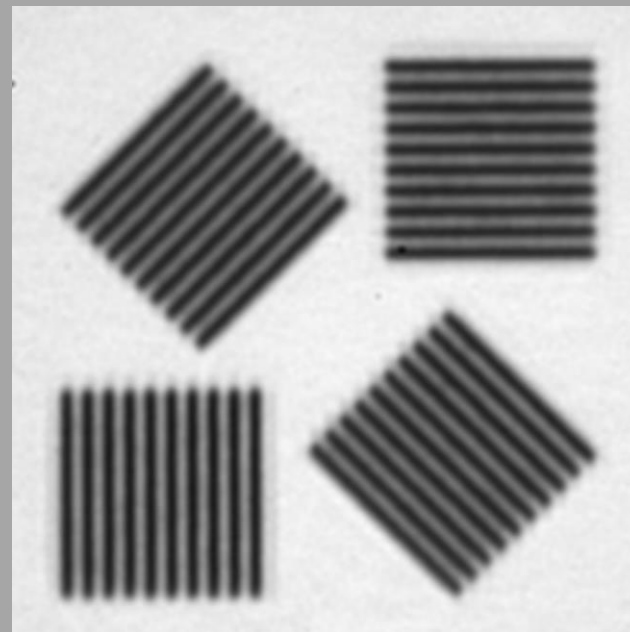
- 0.33 4xNA, regular mask
- imbalanced Quasar

Optimized source



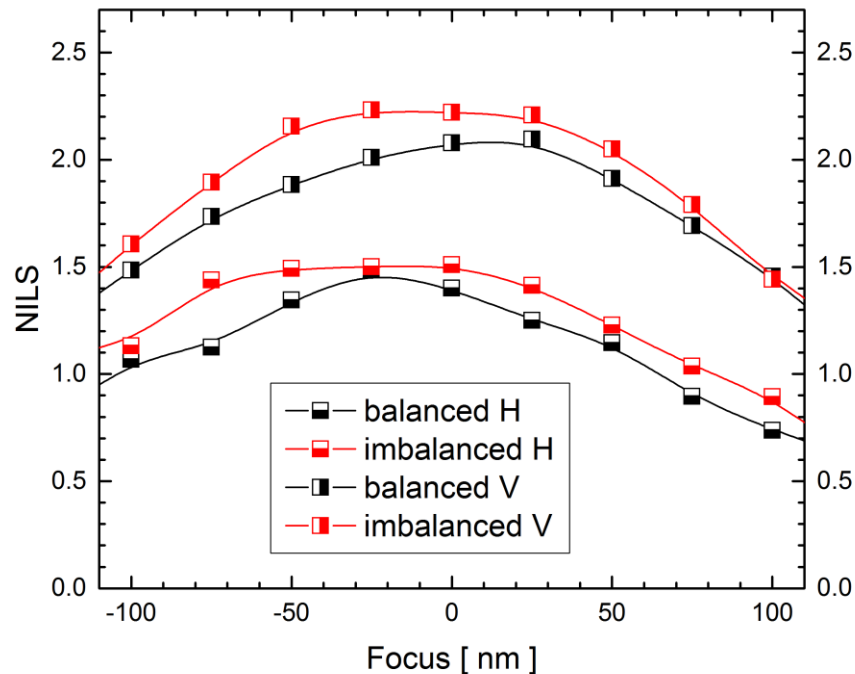
- 0.33 4xNA, Ta-based
- balanced Quasar

- 22.5 nm CD (1x)
- 200 nm (1x)



- 0.33 4xNA, Ta-based
- imbalanced Quasar

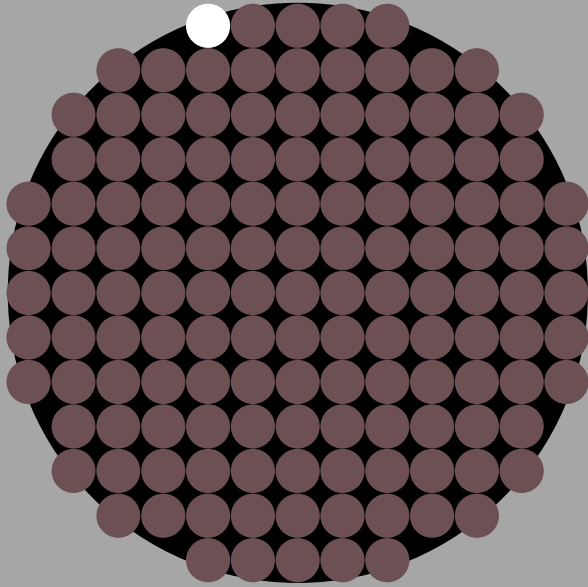
Optimized source



Imbalanced Quasar:

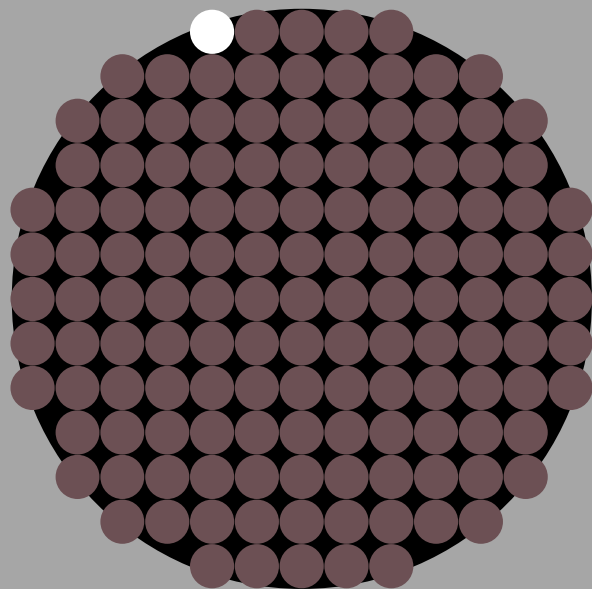
- higher NLS for both grating orientations
- wider focus range

Source Optimization

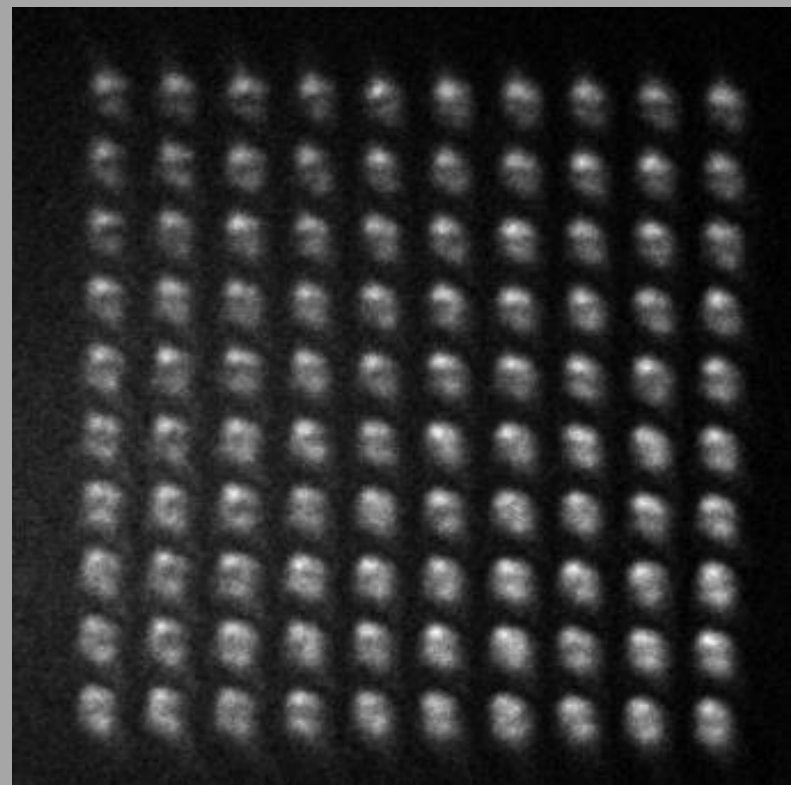


- Pupil Channel α

Source Optimization

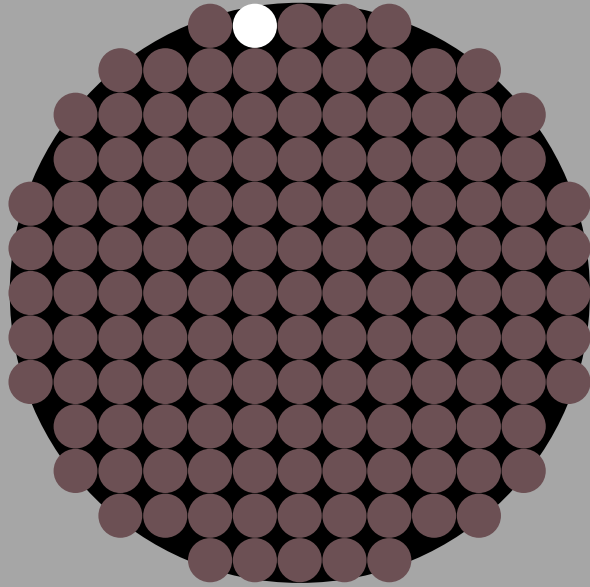


- Pupil Channel α

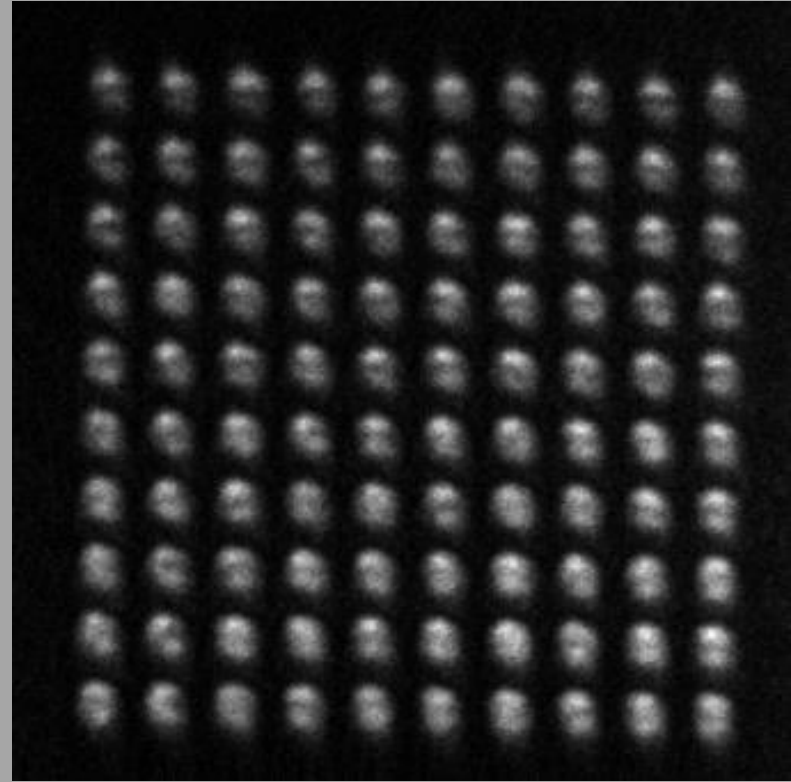


- Image i_a

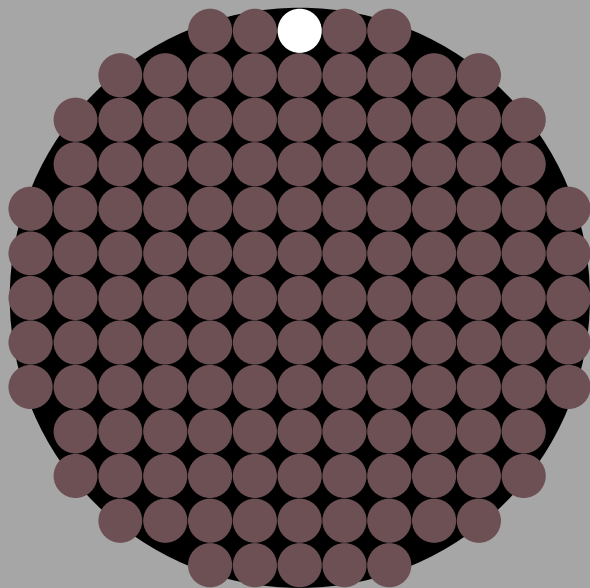
Source Optimization



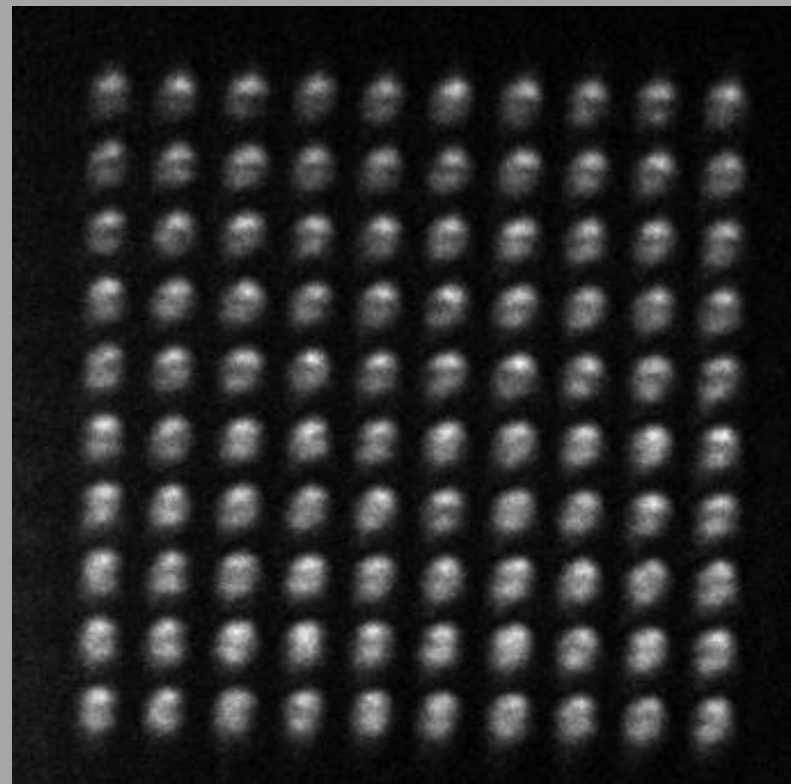
- Pupil Channel α



Source Optimization

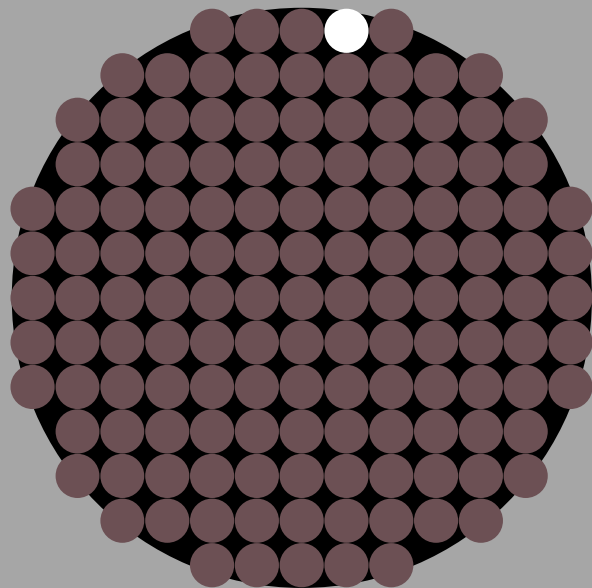


- Pupil Channel α

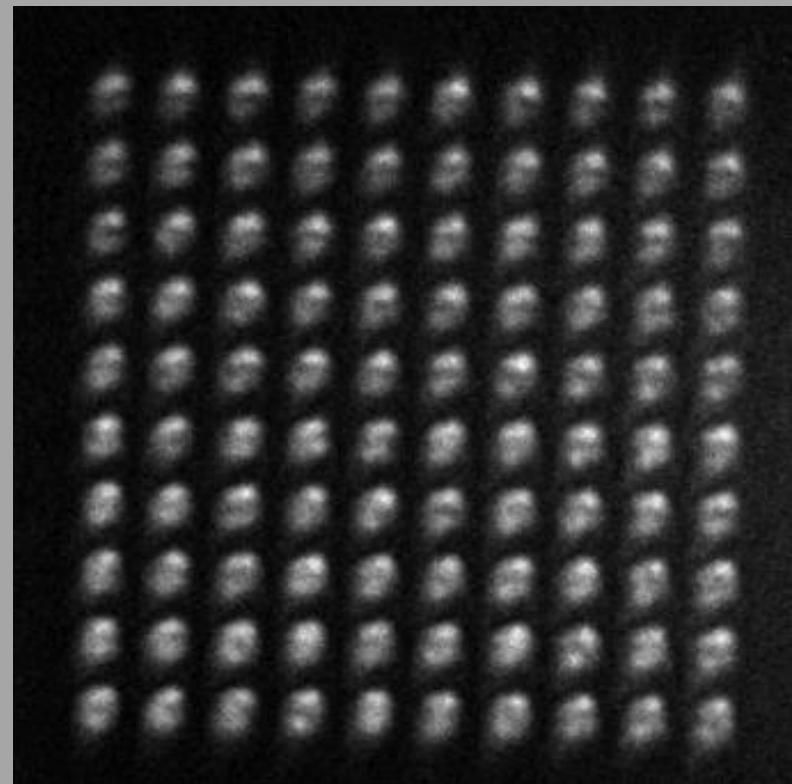


- Image i_a

Source Optimization

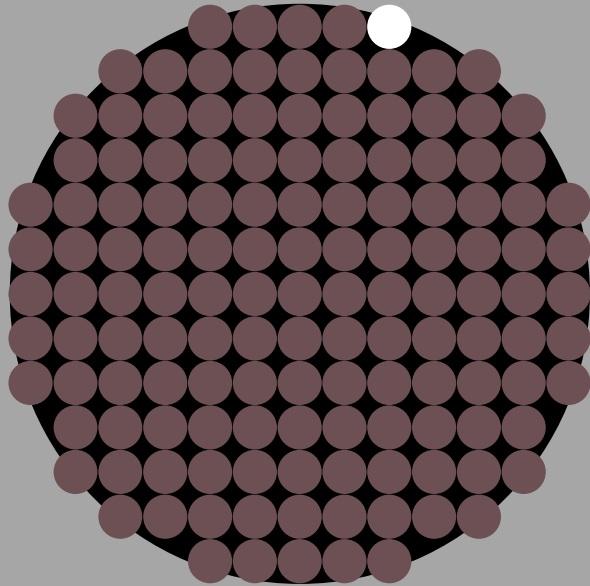


- Pupil Channel α

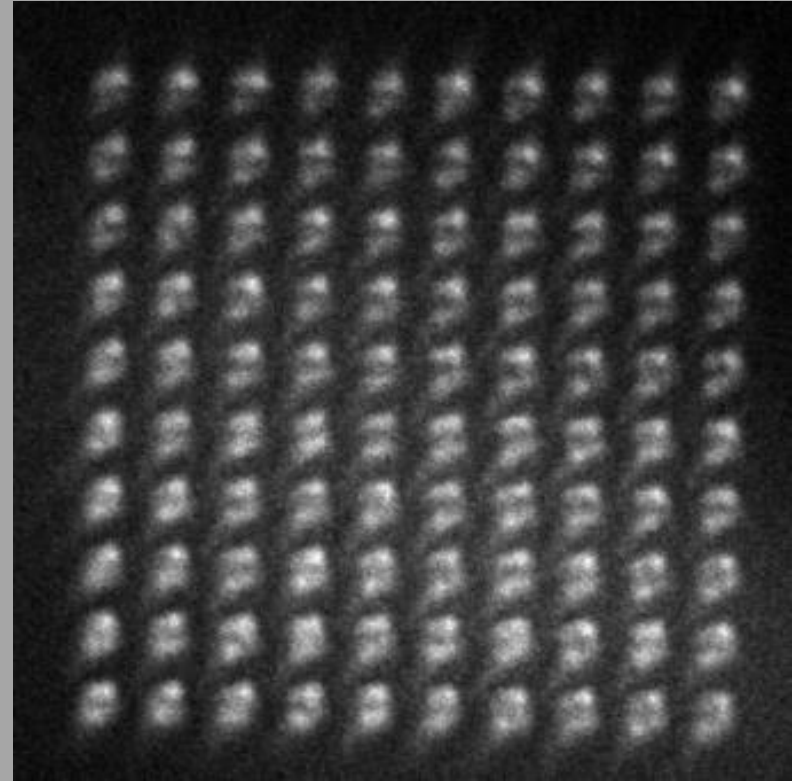


- Image i_a

Source Optimization

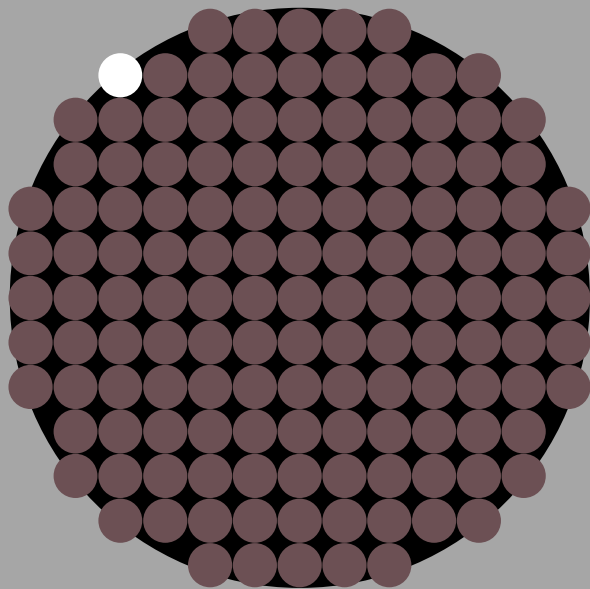


- Pupil Channel α

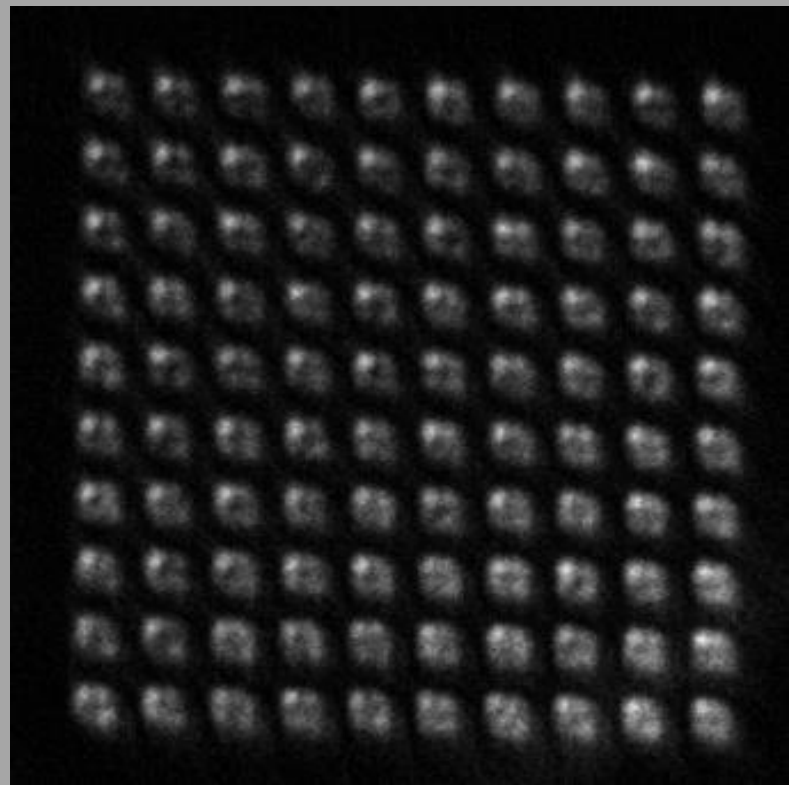


- Image i_a

Source Optimization

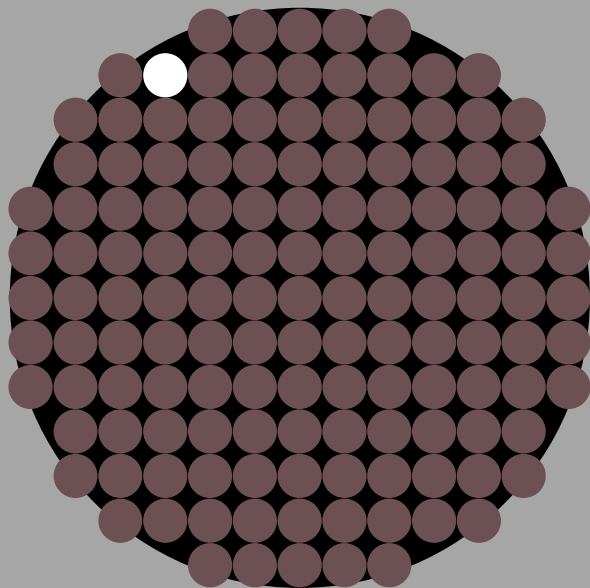


- Pupil Channel α

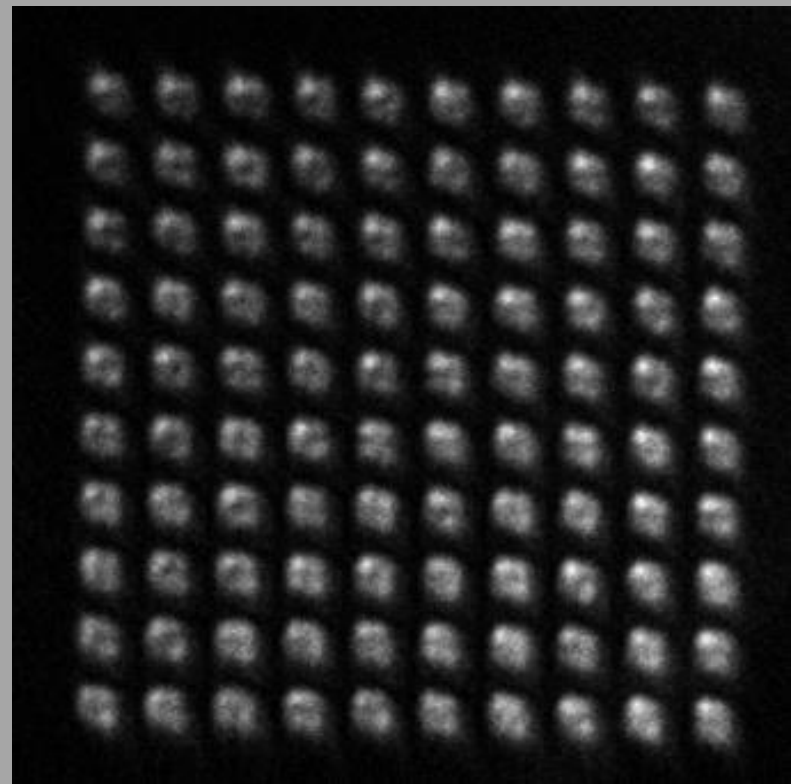


- Image i_a

Source Optimization

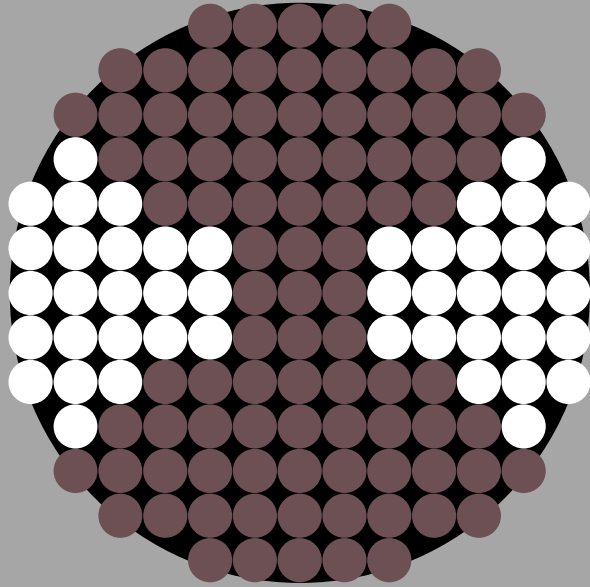


- Pupil Channel α



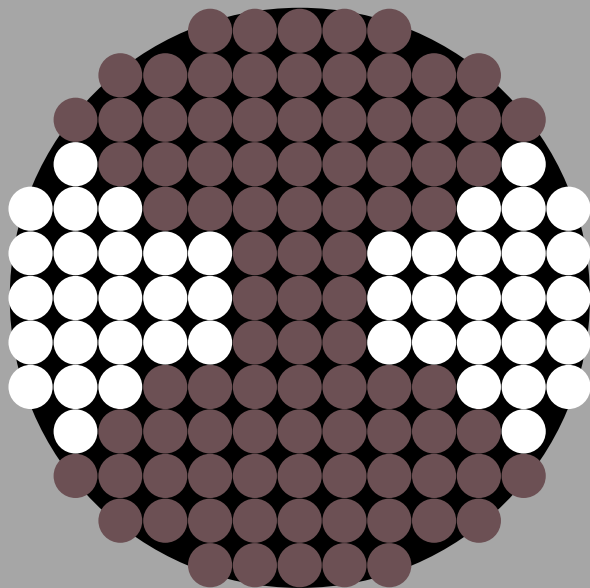
- Image i_a

Source Optimization

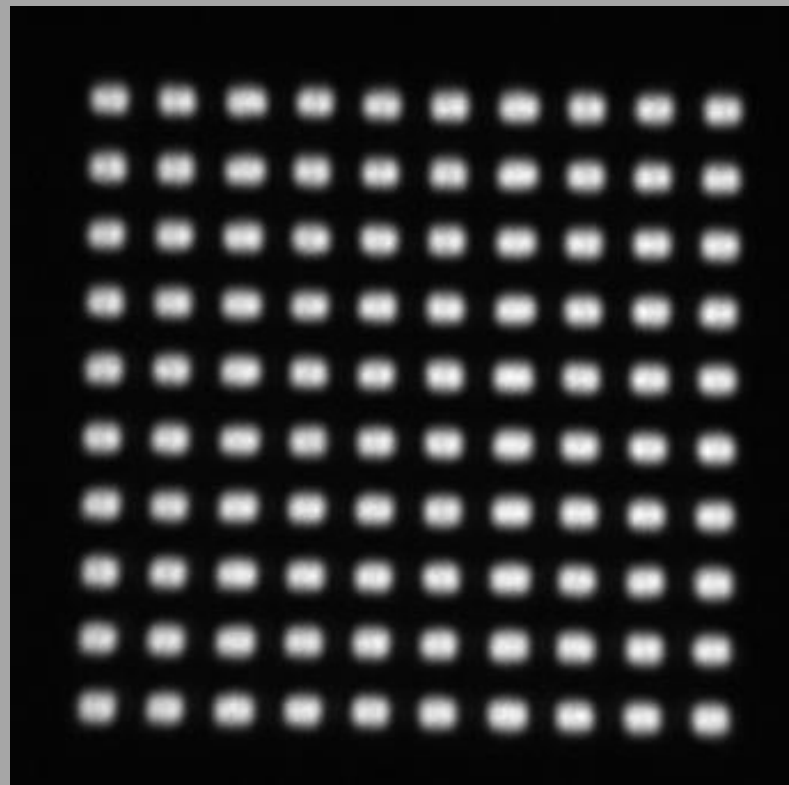


- Pupil

Source Optimization

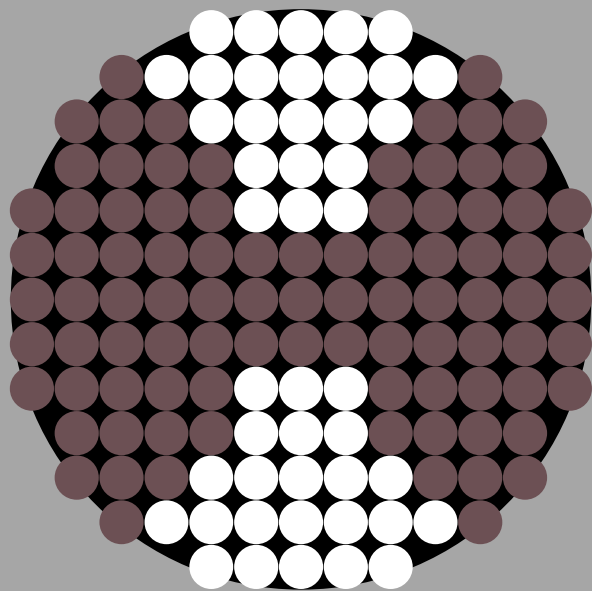


- Pupil

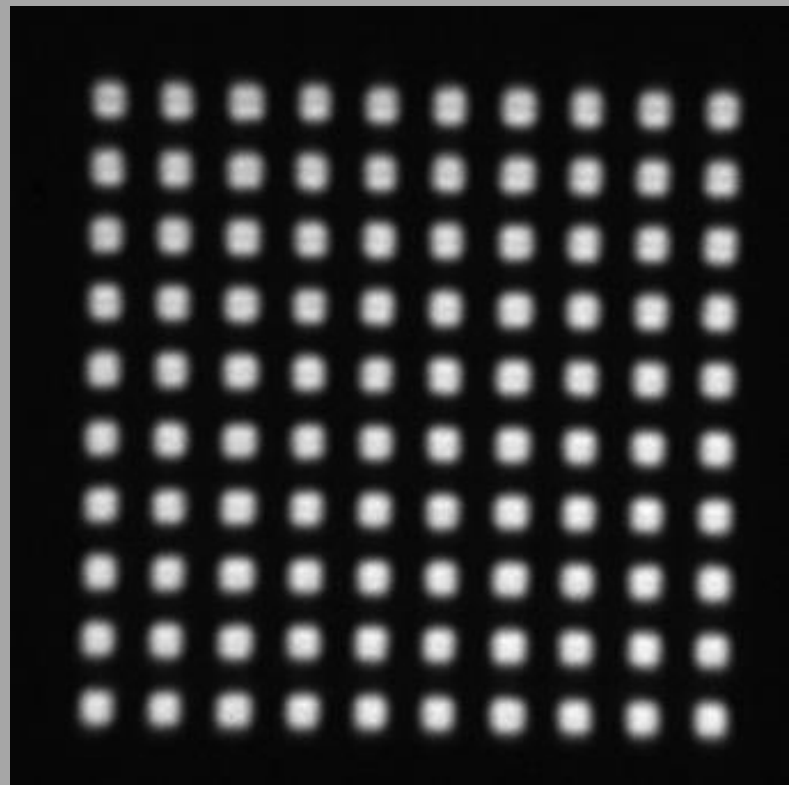


- Image $I = \hat{a}_i$
 a

Source Optimization

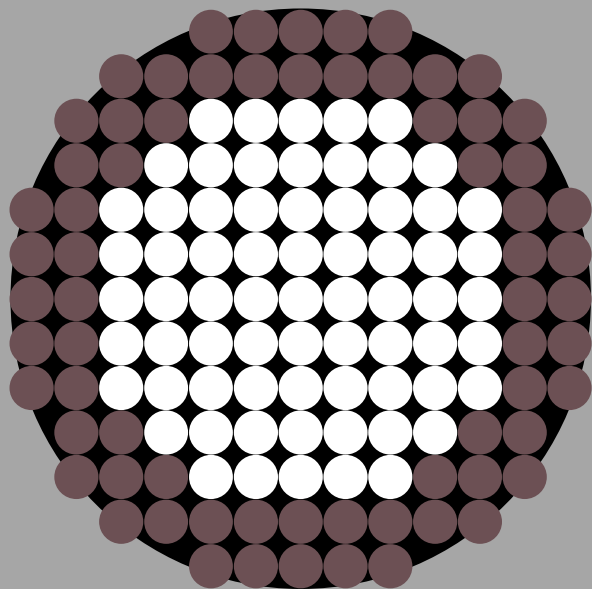


- Pupil

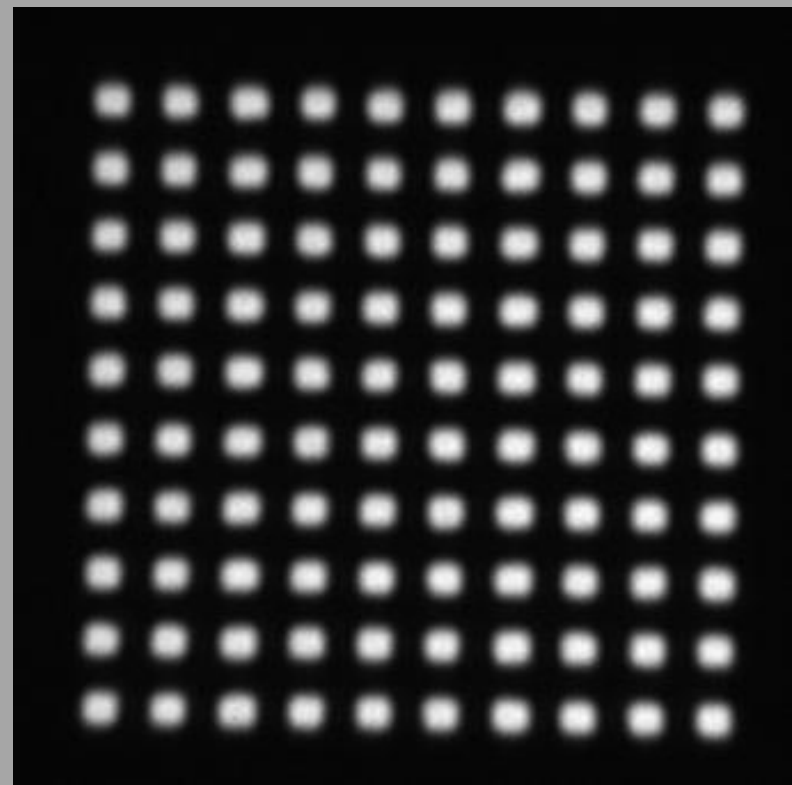


- Image $I = \hat{a} i_a$
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Source Optimization



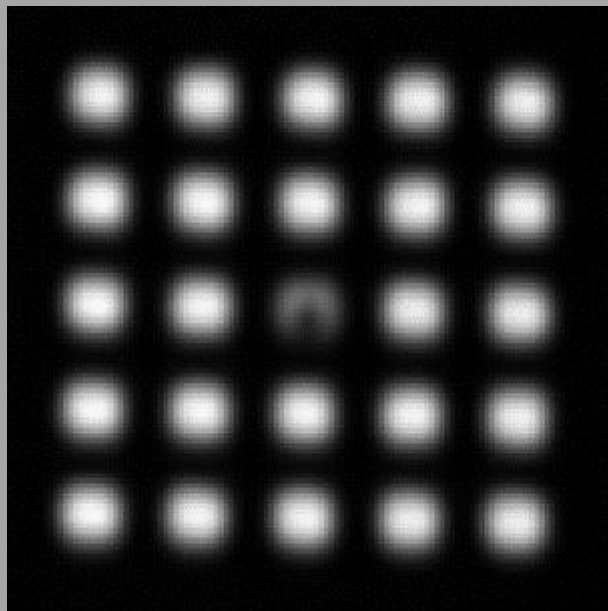
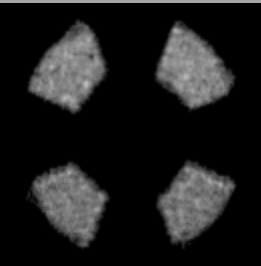
- Pupil



- Image $I = \hat{a}i_a$
 a

Source Optimization

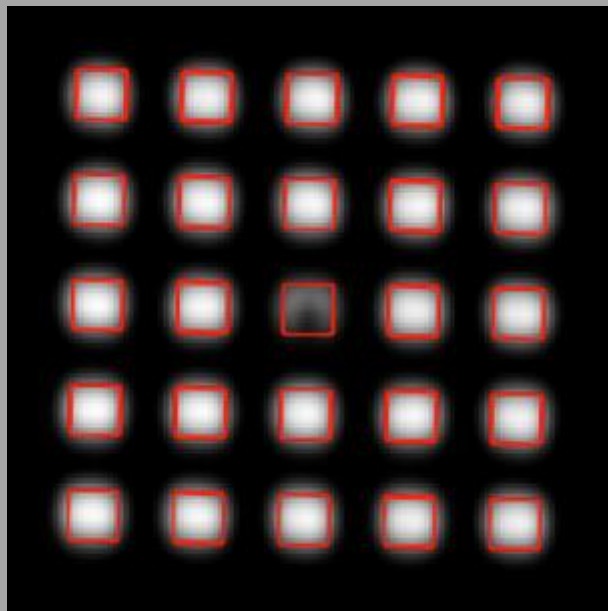
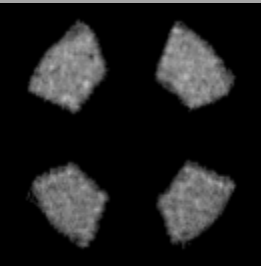
- Quasar



- 40-nm (1x) dense contacts

Source Optimization

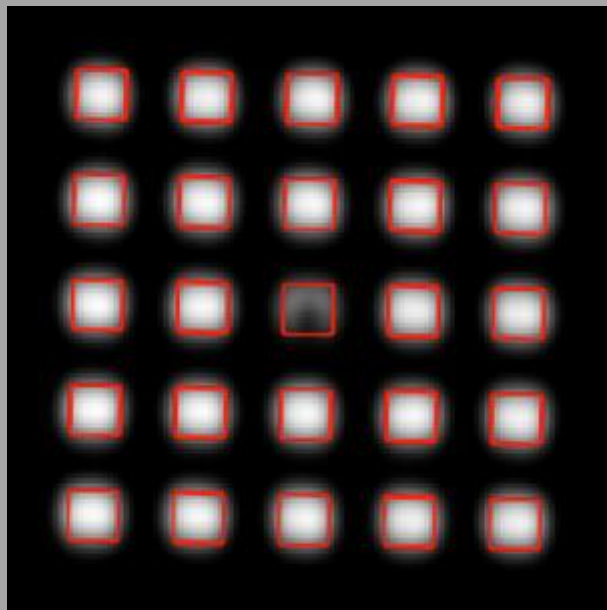
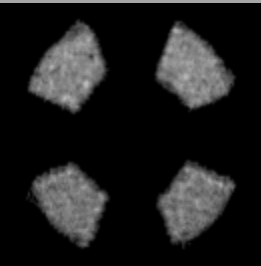
- Quasar



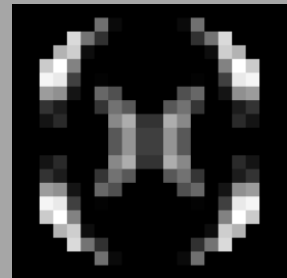
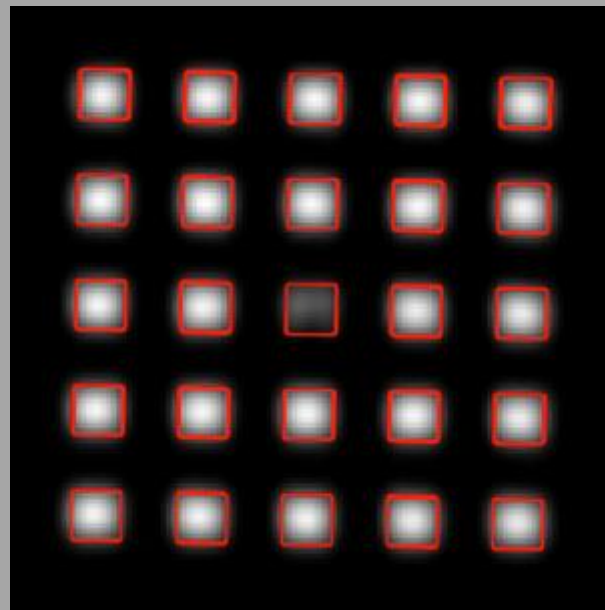
- 40-nm (1x) dense contacts

Source Optimization

- Quasar



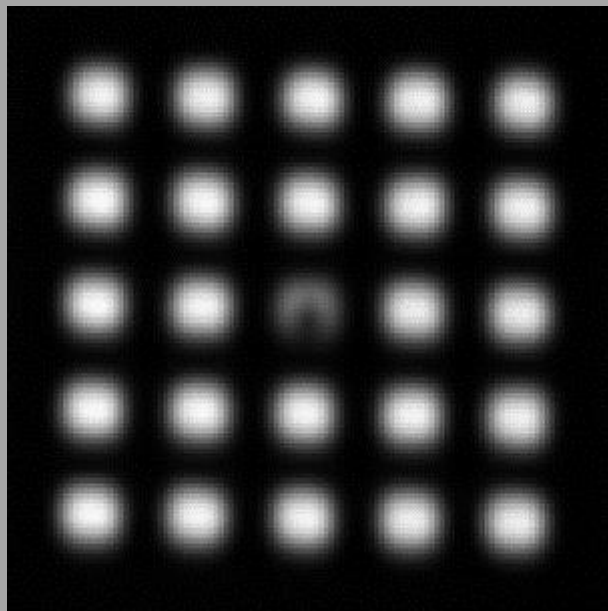
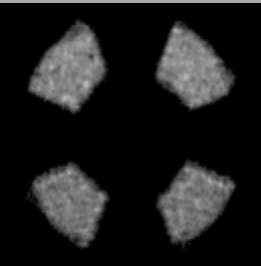
- Freeform Source



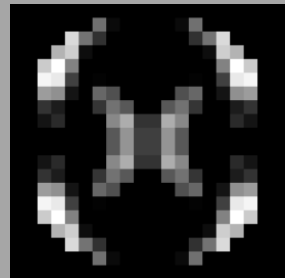
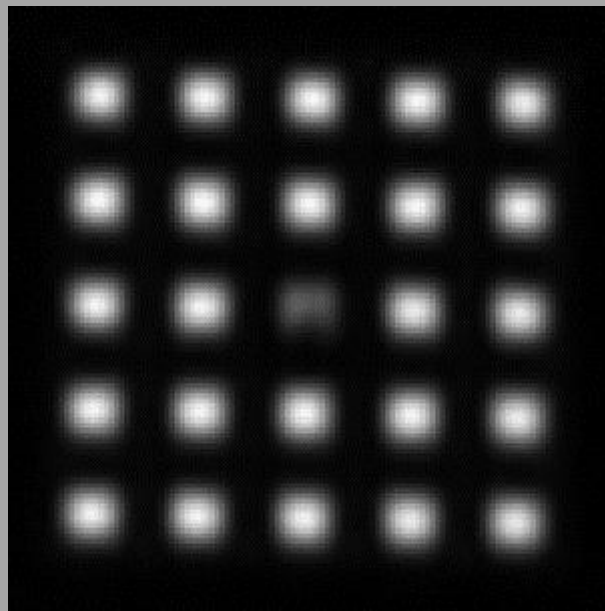
- 40-nm (1x) dense contacts

Source Optimization

- Quasar



- Freeform Source

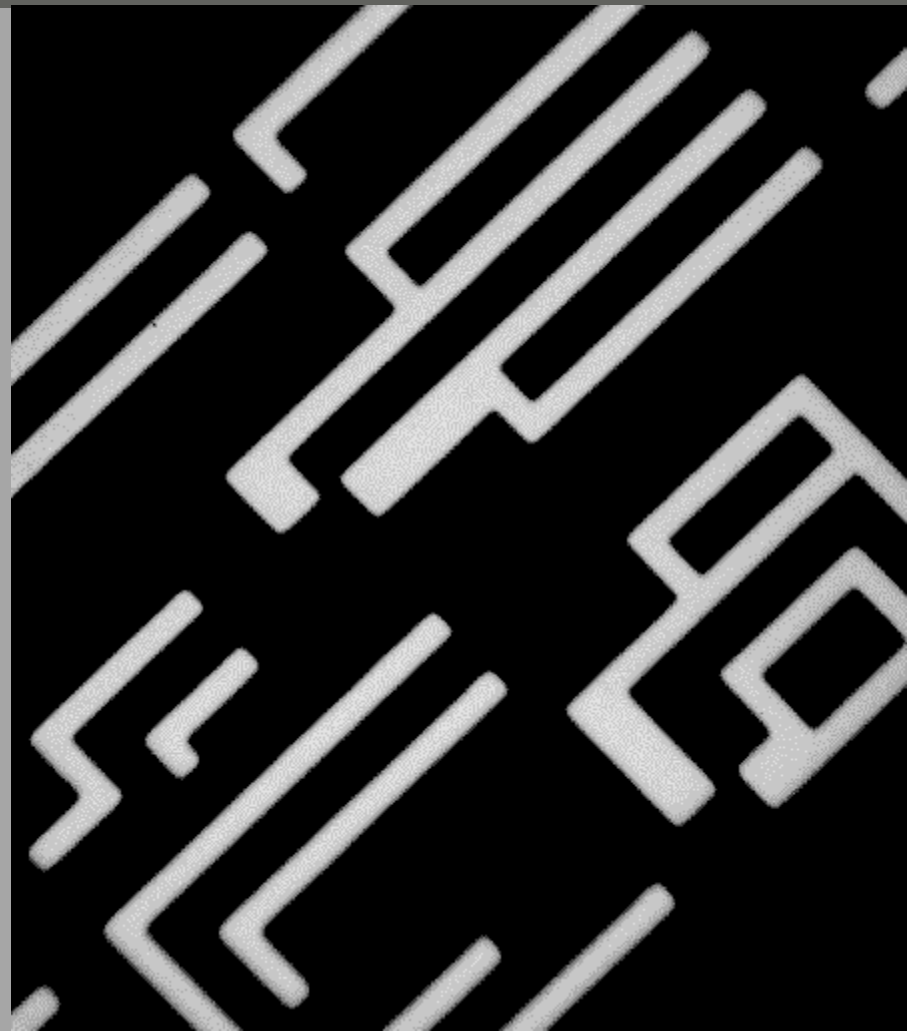


- 40-nm (1x) dense contacts

Summary

SHARP High-NA Actinic Reticle Review Project

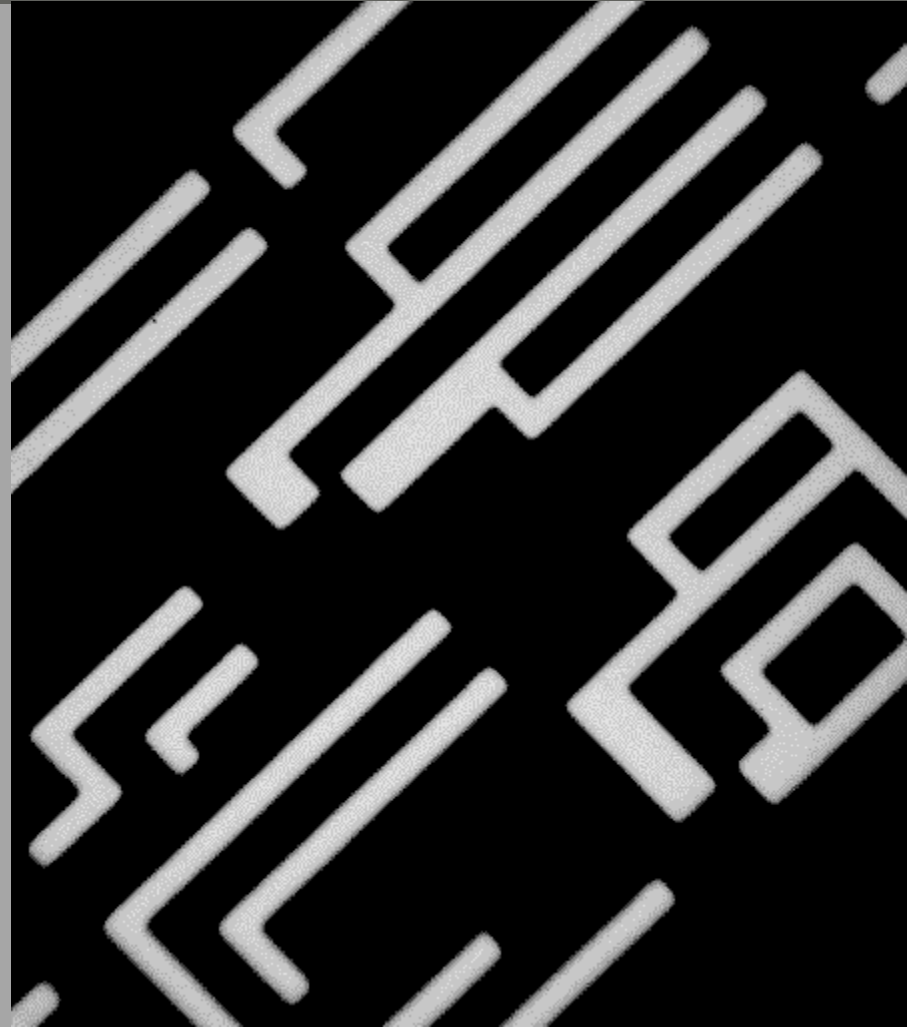
- Emulation of imaging in EUV scanner
- Emulation of anamorphic imaging
- Increased imaging performance with thinner absorber both for 0.33 and 0.55 anamorphic
- Source Optimization demonstration



Thanks to
our users.

Thanks to
INTEL for funding
SHARP operations.

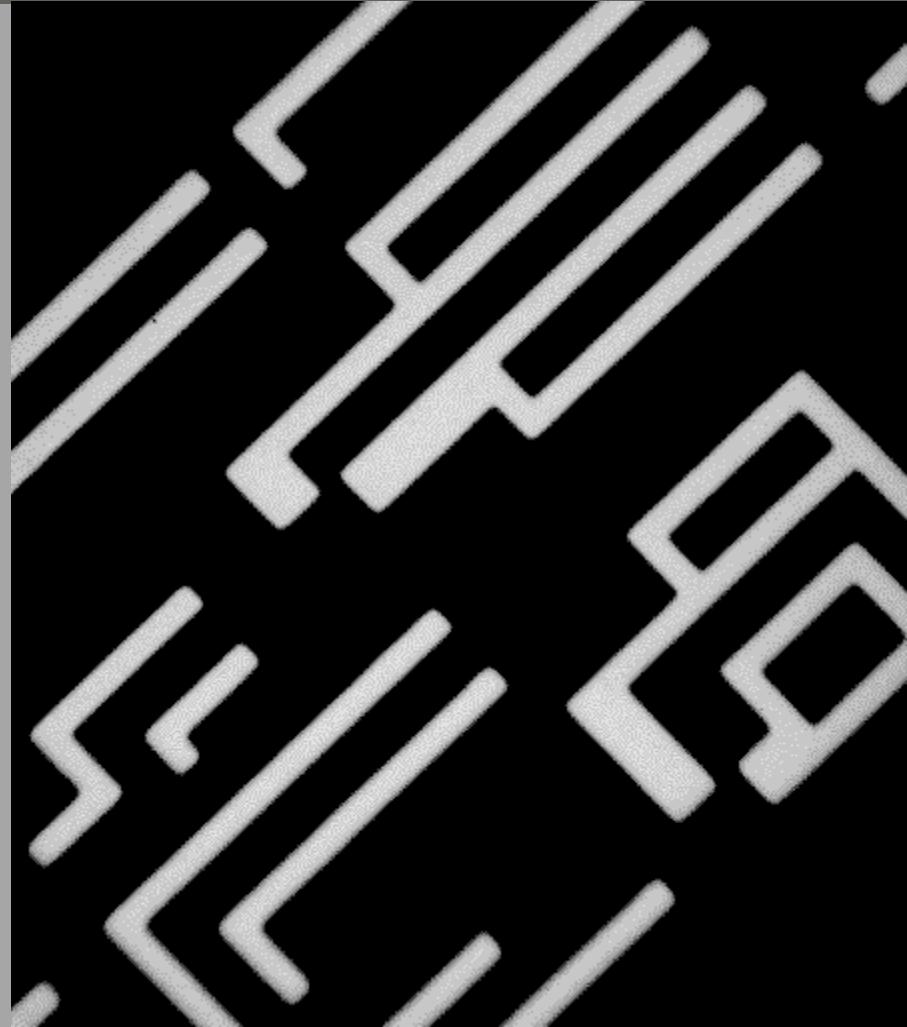
EUV infrastructure at
Berkeley is funded through
the EUREKA program.



Thanks to
our users.

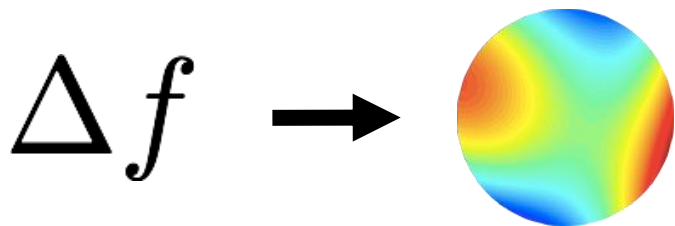
Thanks to
INTEL for funding
SHARP operations.

Thank you!

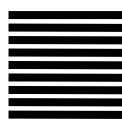


AIS: Characterization of aberrations

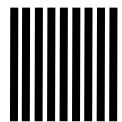
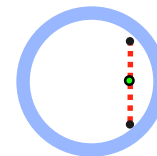
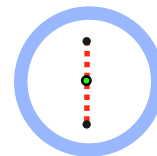
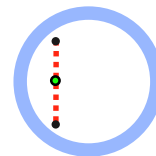
- Through-focus image data of 4 grating orientations and 12 monopole illuminations



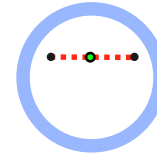
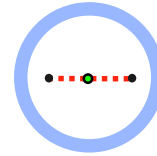
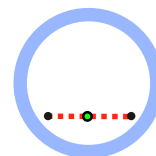
- Aberrations solved from measured focus shifts using least-squares approach



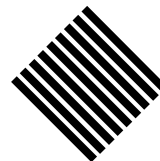
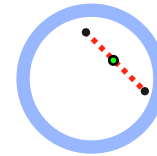
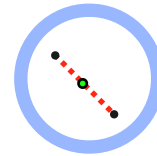
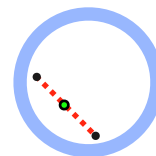
90° (3 points)



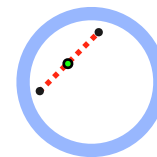
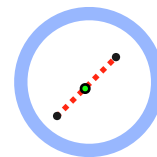
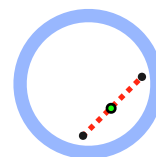
0° (3 points)



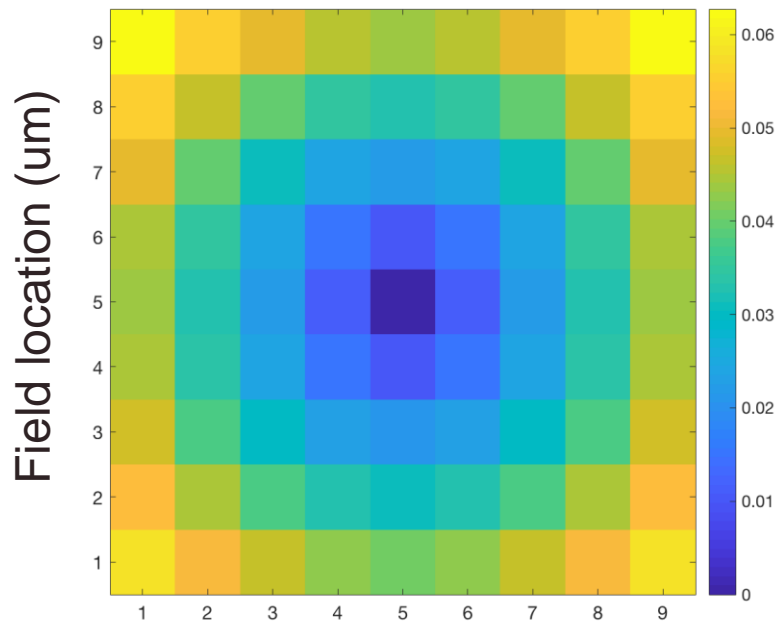
135° (3 points)



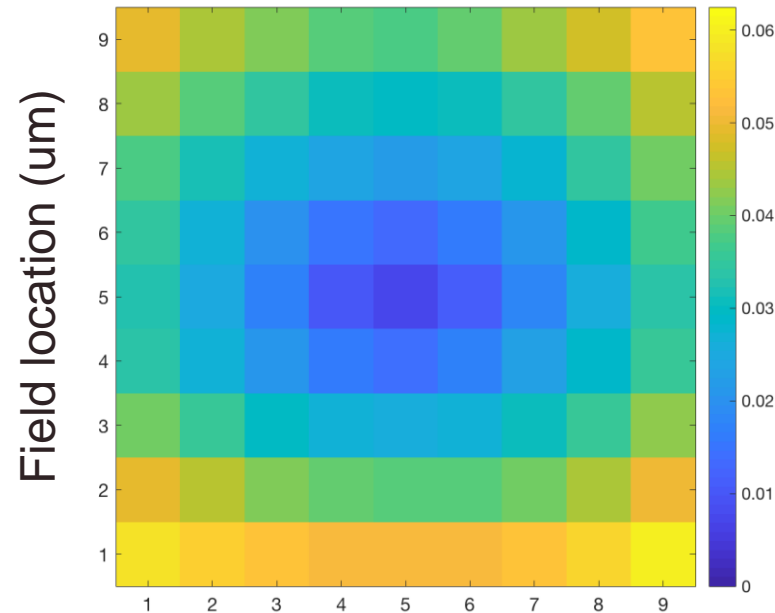
45° (3 points)



Field dependent aberrations



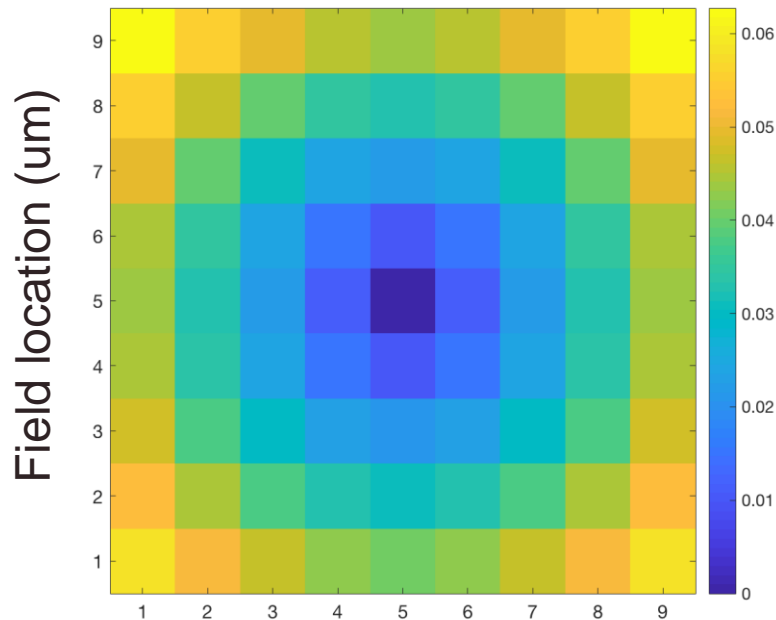
■ Ideal 0.33 4xNA zoneplate



■ AIS measurement

Sweet spot (Z_4 to Z_8) : **7.2 m λ RMS** ($\lambda_{\text{EUV}}/139$)

Field dependent aberrations



Latest measurement

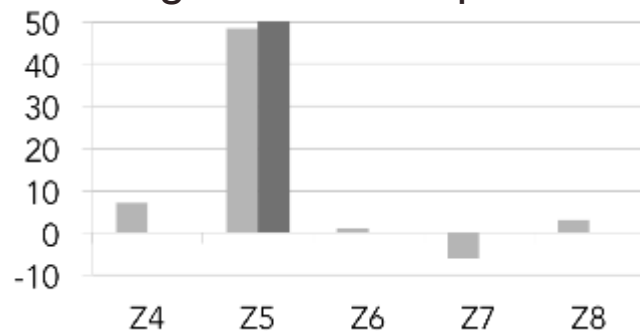
Sweet spot (Z_4 to Z_8) : **4.4 mλ RMS**

- Ideal 0.33 4xNA zoneplate

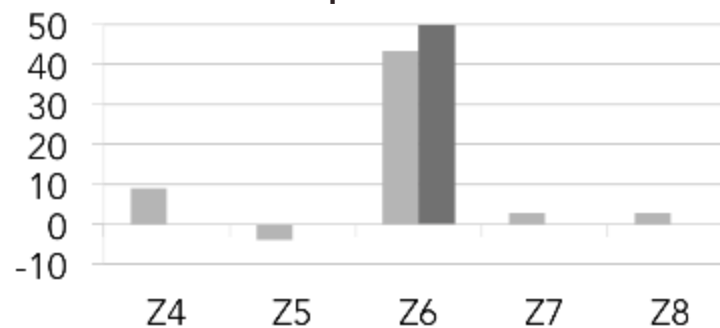
Programmed aberrations

■ programmed
■ measured

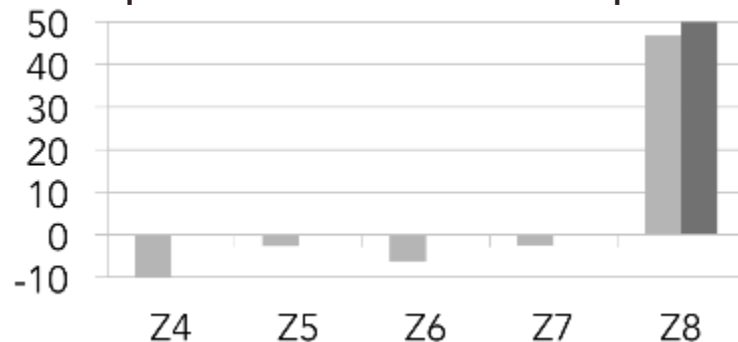
Astigmatism zoneplate



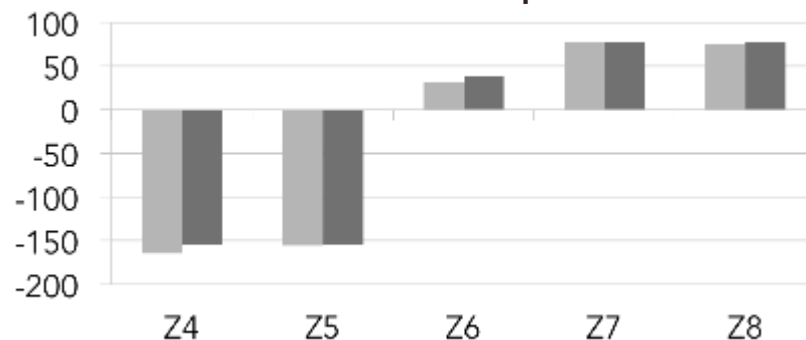
Coma zoneplate



Spherical aberration zoneplate



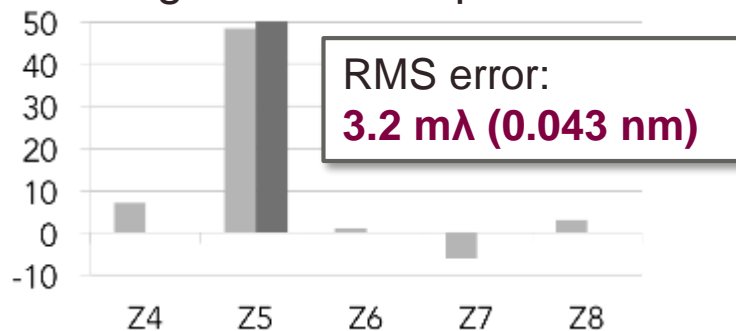
Mixed Zernike zoneplate



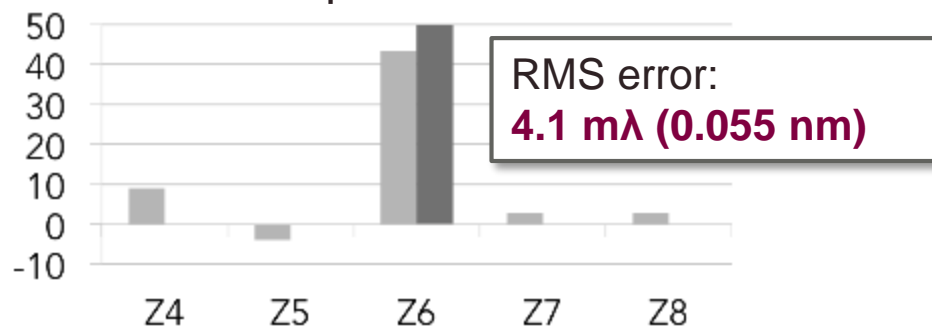
Programmed aberrations

■ programmed
■ measured

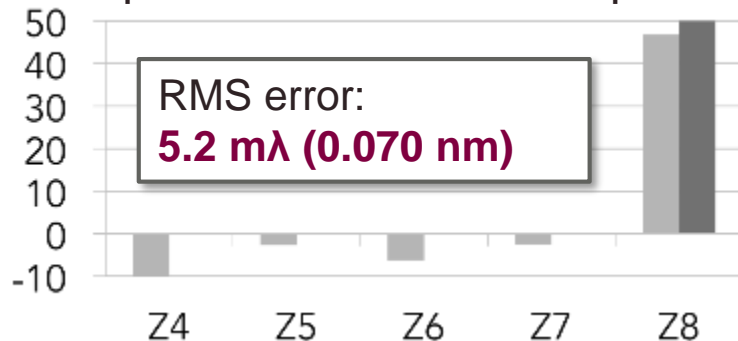
Astigmatism zoneplate



Coma zoneplate



Spherical aberration zoneplate



Mixed Zernike zoneplate

